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Metodología para el análisis de la sostenibilidad de piezas de plástico inyectadas

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Tesis Doctoral

METODOLOGÍA PARA EL ANÁLISIS DE LA SOSTENIBILIDAD DE PIEZAS DE PLÁSTICO INYECTADAS

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Tesis Doctoral

Metodología para el análisis de la sostenibilidad de piezas de plástico inyectadas

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TESIS POR COMPENDIO DE PUBLICACIONES

La siguiente tesis doctoral se presenta como compendio de publicaciones realizadas durante el periodo de desarrollo del trabajo de investigación.

A continuación, se listan las referencias de las publicaciones, ordenadas por fecha de aceptación, indicando el factor de impacto en aquellas revistas indexadas JCR, así como los congresos internacionales:

Revistas JCR:

- Elduque, A.; Javierre, C.; Elduque, D.; Fernández, Á. LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process. ***Sustainability*** **2015**, ***7***, 3792-3800. **Q3**, 62/104, Environmental Studies, 1,343.
- Elduque, A.; Elduque, D.; Javierre, C.; Fernández, Á.; Santolaria, J. Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts. Journal of Cleaner Production **2015**, *108*, 80-89, **Q1**, 16/225, Environmental Sciences, 4,959.
- Elduque, A.; Elduque, D.; Clavería, I.; Javierre, C; Influence of material and injection molding machine's selection on the electricity consumption and environmental impact of the injection molding process: an experimental approach. International Journal of Precision Engineering and Manufacturing Green Technology, **2018**, *5*, Nº 1, 13-28, **Q1**, 8/130, Mechanical Engineering, 3,494.

Congresos Internacionales:

- Elduque, A.; Elduque, D; Pina, C.; Javierre, C.; Fernández, Á. LCA Software for Environmental Impact Assessment of Injected Mould Plastic Parts. 27th EMSS 2015, European Modelling & Simulation Symposium, 21-23 Septiembre **2015**, Código Proceedings publicado en Scopus: 116186, 359-367.

Por último, se ha presentado al congreso online "The 3rd International Electronic Conference on Materials Sciences" que se celebrará del 14 al 28 de Mayo de 2018, el siguiente trabajo:

- Elduque, A.; Elduque, D.; Clavería, I.; Javierre, C; Empirical Model to estimate the Electricity Consumption of the Polymer Material Injection Molding Manufacturing Process. The 3rd International Electronic Conference on Materials Sciences, **2018**.

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INTRODUCCIÓN GENERAL

La industria del plástico en Europa comenzó a valorar el impacto ambiental de los plásticos hace más de veinticinco años, [1]. La conciencia medioambiental de la sociedad está aumentando en todo el mundo [2], siendo la amenaza del calentamiento global una de las principales razones [3]. Esta preocupación por nuestro entorno ha promovido el uso y desarrollo de diferentes metodologías en búsqueda de un desarrollo sostenible. El análisis de ciclo de vida (ACV) es una metodología que se emplea para calcular el impacto ambiental de productos, procesos o servicios. Los resultados obtenidos mediante estos estudios se analizan para poder identificar las áreas prioritarias sobre las que se ha de actuar [4]. Trabajando sobre éstas, los investigadores y diseñadores pueden llegar a conseguir una mejora en este aspecto, haciendo los productos y procesos más respetuosos con el medioambiente.

Los procesos de transformación de materiales termoplásticos se vienen desarrollando, optimizando y utilizando en la fabricación de componentes desde hace décadas, en todos los sectores productivos. Más recientes son las presiones sociales y normativas (ISO 14006), [5], que tienden a introducir el criterio de mínimo impacto ambiental en el desarrollo de productos y en los procesos empleados en su fabricación. En este campo, que cada vez va teniendo mayor peso, es necesario hacer un gran esfuerzo de investigación para el desarrollo de metodologías de trabajo que permitan la optimización de los componentes, incluyendo sus procesos de fabricación.

Para la cuantificación del impacto ambiental de un componente, conjunto mecánico o proceso es necesario hacer un análisis del mismo, de cara a considerar todos los aspectos que intervienen en tal impacto ambiental. La cuantificación de la repercusión económica, conlleva un esfuerzo de investigación añadido, pero factible, pues ambos cálculos suponen la consideración de todos los factores que intervienen: materiales, procesos, etc.

Esta tesis se centra en el análisis de la sostenibilidad de las piezas de plástico inyectadas, considerando dos dimensiones, el impacto ambiental y económico y focalizándose especialmente en el análisis del proceso de fabricación de la inyección de plásticos, dentro del análisis de ciclo de vida completo.

A lo largo de la investigación, se han realizado publicaciones científicas recogiendo los resultados de las distintas fases del trabajo. En primer lugar, en el artículo de la revista Sustainability se recoge el estudio realizado sobre las bases de datos EcoInvent utilizadas en el inventario de los análisis de ciclo de vida. En dicho artículo, se desglosan los datos con los que se genera el inventario de la base de datos para el proceso de inyección de plásticos y se realiza un análisis de sensibilidad de los resultados, modificando el caso genérico de EcoInvent. Mediante este análisis, se pone de manifiesto la necesidad de un estudio pormenorizado del proceso, para poder detectar acciones de mejora o evitar contar doblemente aspectos del inventario en la realización de un ACV. A su vez, se detecta el consumo eléctrico como el principal factor en los resultados de impacto ambiental, y también del coste económico. Por ello, en paralelo, se realizan medidas experimentales del consumo eléctrico durante el proceso de inyección de plásticos. En un siguiente paso, se propone una metodología alternativa para evaluar el impacto del proceso, modificando la base de datos de EcoInvent y sustituyendo los valores de consumo eléctrico por medidas experimentales. Esta metodología se presenta en el segundo artículo publicado en la revista Journal of Cleaner Production. El consumo eléctrico del proceso de ocho piezas de polietileno de alta densidad inyectadas en distintas máquinas de inyección, se obtiene mediante un analizador de redes, obteniendo un rango de consumos entre 0,4 y 2,6 kWh/kg, frente al valor constante de 1,47 kWh/kg considerado por EcoInvent.

Dada la importancia de contar con medidas experimentales, se ha realizado un gran esfuerzo en contar con datos reales de consumos eléctricos. Para ello se han llevado a cabo medidas en distintas fábricas, como ZALUX, la fundación aiTIIP y la empresa CONTENUR. Gracias a ello se recopilaron las 36 medidas incluidas en el tercer artículo publicado en revista indexada International Journal of Precision Engineering and Manufacturing Green Technology. En este último artículo se establecen las principales tendencias observadas en las medidas experimentales, extrayendo las primeras conclusiones de la investigación.

De forma paralela se ha trabajado en la realización de un software que permita calcular de forma detallada el análisis de ciclo de vida de una pieza de plástico inyectada. Esta aplicación permite de forma sencilla introducir los datos de la pieza, y desglosar la importancia que tiene sobre el impacto ambiental y el coste económico en cada fase de vida del producto. Una primera versión de la aplicación fue presentada en el congreso internacional celebrado en Bergeggi en Septiembre de 2015 (27th EMSS 2015, European Modelling & Simulation Symposium). Este software ha sido registrado en el registro de la Propiedad Intelectual del Gobierno de Aragón. Además, ha sido utilizado por estudiantes de la EINA en tres cursos académicos del Máster Universitario en Ingeniería de Diseño de Producto, concretamente en las prácticas de la asignatura "Desarrollo Avanzado de Producto".

Por último, en el congreso "The 3rd International Electronic Conference on Materials Sciences" se muestra un modelo empírico basado en las medidas experimentales realizadas durante esta tesis doctoral, cerrando la unidad temática de la investigación. Mediante el uso de este modelo es posible la estimación del consumo eléctrico del proceso de inyección de forma más ajustada que usando bases de datos como EcoInvent, en función del tipo de máquina de inyección utilizada, el material termoplástico y los parámetros del proceso, en el caso de que no sea posible la realización de una medida experimental.

Índice

LISTADO DE FIGURAS

LISTADO DE TABLAS

Capítulo 1

INTRODUCCIÓN

1. INTRODUCCIÓN

La tesis doctoral "Metodología para el análisis de la sostenibilidad de piezas de plástico inyectadas" se ha desarrollado dentro del grupo de investigación i+, englobado en el Área de Ingeniería Mecánica dentro del Departamento de Ingeniería Mecánica de la Escuela de Ingeniería y Arquitectura de la Universidad de Zaragoza y ha sido dirigida por el Dr. Carlos Javierre Lardiés. Esta tesis se presenta como compendio de publicaciones, las cuales se muestran íntegramente en el capítulo 9 de este documento.

En esta memoria se recoge de forma resumida cuáles han sido los objetivos del trabajo, la justificación de la investigación, su metodología, resultados, conclusiones y futuras líneas de investigación. Cabe destacar que los contenidos de esta tesis comenzaron con el proyecto final de carrera de la doctoranda " Análisis del impacto ambiental del proceso de inyección para ser considerado como criterio de diseño y de selección de máquina. Aplicación a una herramienta informática " finalizando con el mismo la licenciatura de Ingeniería Industrial y posteriormente con el trabajo fin de máster "Análisis de Ciclo de Vida de una pieza de plástico inyectado para su optimización desde el punto de vista de impacto medioambiental y económico. Aplicación a una herramienta informática", del Máster Universitario en Ingeniería Mecánica de la Universidad de Zaragoza.

En la actualidad, el impacto causado por la actividad del ser humano sobre el medioambiente se ha convertido en uno de los problemas que la sociedad debe afrontar en busca de soluciones para combatir el cambio climático. En los últimos años conceptos como ecodiseño, huella de carbono, economía circular, están cobrando fuerza dentro de una sociedad más concienciada con los problemas medioambientales, fomentados también por el aumento de la exigencia de la legislación en este ámbito. Ejemplo de ello son las directivas europeas que regulan el uso de sustancias tóxicas, ROHS y REACH, [6], [7], la directiva WEEE sobre el fin de vida de los productos eléctricos o electrónicos [8] o aquellas que promueven las prácticas de ecodiseño, [9], [10].

Dentro del ámbito científico se han generado herramientas y metodologías que permiten evaluar de una forma sistemática los impactos ambientales tanto de productos, procesos o servicios, a través de la aplicación de la metodología de Análisis de Ciclo de Vida.

En este nuevo escenario, donde la presión medioambiental va en aumento, y el coste de la energía se prevé al alza, [11], las empresas deben realizar evaluación de riesgos y buscar qué nuevas oportunidades se presentan en la búsqueda de reducción del impacto ambiental de sus actividades, [12].

Una de las industrias más importante a nivel global es la industria de los plásticos. Estos materiales son muy polivalentes, siendo sus aplicaciones variadas, desde el sector del embalaje, que representa casi el 40% de la demanda de plásticos en Europa, pasando por el sector de la construcción, el automóvil o los productos eléctricos y electrónicos, [13]. Uno de los principales procesos de fabricación para el material termoplástico es la inyección de plásticos, debido a la precisión de éste y su rentabilidad para volúmenes altos de producción, [14], [15]. Es por ello que el estudio en detalle de su impacto, puede reportar grandes beneficios ambientales y llevar asociado a su vez reducciones de coste económico.

1.1. JUSTIFICACIÓN DE LA TESIS DOCTORAL

La industria está teniendo que enfrentarse a una creciente presión para reducir su huella de carbono e impacto ambiental, especialmente debido a la influencia del cambio climático y al consiguiente incremento de la concienciación en la sociedad. Este hecho, las nuevas regulaciones y el creciente coste de la energía, provocan que las empresas deban buscar el camino de la sostenibilidad.

Las metodologías y herramientas desarrolladas en los últimos años, como el ACV; los softwares como SimaPro o las bases de datos para realizar inventarios como EcoInvent, son necesarias para identificar áreas críticas sobre las que focalizar acciones de mejora.

Aunque es claro el creciente interés en conseguir una industria y unos procesos más cuidadosos con el medioambiente, se ha observado durante la revisión del estado del arte que existe una falta de datos experimentales en la literatura, a la hora de generar el inventario para el ACV, en especial, en los procesos de fabricación; por lo que en este trabajo se hace un mayor énfasis en el proceso de inyección de plásticos y su consumo eléctrico.

A lo largo de la investigación se ha abordado desde distintas perspectivas el estudio del consumo eléctrico del proceso de inyección, inicialmente durante la fase de estudio del arte, desde un punto de vista teórico, para posteriormente centrar los esfuerzos en la realización de medidas experimentales, debido a la alta variabilidad observada según las características de pieza y máquina, y la importancia de este valor en el impacto total, económico y ambiental; para, finalmente, tratar esos resultados experimentales, construyendo un modelo empírico para la estimación del consumo eléctrico.

1.2. OBJETIVOS Y METODOLOGÍA

En primer lugar, en una fase preliminar de la investigación y tras la revisión del Estado del Arte, se identifica un campo con potencial de mejora por lo que se plantea el estudio en detalle del proceso de inyección de plásticos, comenzando por el análisis de los datos empleados actualmente por bases de datos empleadas en los ACV como es EcoInvent.

Posteriormente se abarca el desarrollo de una metodología de cálculo desde el punto de vista teórico, que se busca implantar en una aplicación informática para facilitar la obtención de resultados.

Con la implementación de esta aplicación se persiguen los siguientes objetivos:

- Selección de la máquina óptima para un determinado molde o pieza
- Permitir al diseñador introducir en el cálculo del coste y el impacto ambiental de una pieza de plástico inyectada el proceso de inyección al detalle.
- Aportar sensibilidad en la toma de decisiones, ante cambios de material, composición de aditivos o parámetros relacionados con el proceso de fabricación, para confirmar su viabilidad en ambos campos, antes de su implantación.
- Análisis global de la sostenibilidad de una pieza de plástico inyectada, teniendo en cuenta todas las fases del ciclo de vida, y contemplando la influencia de las distintas variables en dos dimensiones, la medioambiental y la económica.

Ya en las fases iniciales de la investigación se detecta el consumo eléctrico como el factor principal sobre el que trabajar para reducir impacto ambiental y económico. Es por ello que en paralelo se propone realizar medidas en fábrica, con las que posteriormente plantear un modelo de estimación empírico.

Para la consecución de estos objetivos ha sido necesario adquirir conocimiento en los siguientes campos:

- Estado del arte en el campo de impacto medioambiental, y más concretamente en el ámbito de los procesos de fabricación y del proceso de inyección de plásticos en particular.
- Aprendizaje del manejo del software SimaPro y la base de datos EcoInvent.
- Uso de las metodologías ReCiPe y CML para el cálculo de impacto ambiental.
- Aprendizaje de Visual Basic . NET para el desarrollo de la aplicación informática.
- Realización de medidas experimentales en Zalux, aiTIIP y Contenur.

1.3. ESQUEMA Y DESARROLLO DEL DOCUMENTO

Una vez presentada la temática y fijados los objetivos, la memoria del contenido de la tesis doctoral se ha estructurado de la siguiente manera:

- Revisión del Estado del Arte
- Análisis de Ciclo de Vida
- Medidas experimentales
- Modelo empírico
- Conclusiones
- Líneas futuras de investigación
- Publicaciones
- Anexos

Capítulo 2

ESTADO DEL ARTE

2. ESTADO DEL ARTE

Tal y como se ha mencionado al inicio de este documento, la legislación medioambiental se ha visto incrementada recientemente, con la publicación de diversas Directivas Europeas como la directiva WEEE, en la que se aborda la gestión de los residuos de aparatos eléctricos o electrónicos, [8], o directivas relacionadas con el Ecodiseño, donde se establecen requerimientos de diseño dirigida a productos, que, o bien están relacionados, o hacen uso de energía, [9], [10].

A su vez, aspectos como la desmaterialización, la reciclabilidad, el fácil desmontaje serán puntos a reforzar en los próximos años, y se verán reflejados en nuevas directivas con el objetivo de acercarnos a una economía circular, que resulte más eficiente en el uso de los recursos naturales.

De la mano de estos cambios legislativos, ha ido el desarrollo de metodologías y herramientas de evaluación para este nuevo criterio ecológico.

La eco brújula es una herramienta gráfica, donde se evalúan en una escala distintos parámetros para analizar el estado de diseño de un producto, [16]. Otras herramientas, como la denominada matriz MET, son cualitativas, donde se registran qué materiales, energía y sustancias tóxicas son utilizadas en la manufactura de un determinado producto, [17].

Para realizar un estudio de manera cuantitativa, la metodología más reconocida en el ámbito científico es el Análisis de Ciclo de Vida (ACV). El procedimiento en la elaboración de este tipo de estudios queda recogido dentro de las normativas ISO 14040 y 14044, [18], [19].

En la Figura 1, se muestran los cuatro pasos en la realización de un ACV.

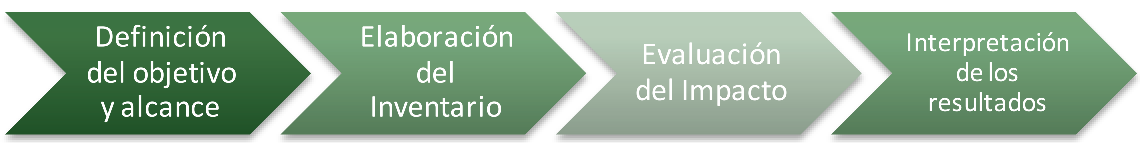

FIGURA 1: PASOS EN LA REALIZACIÓN DE UN ACV

De forma general, para un producto se han de analizar las fases de vida mostradas en la Figura 2.

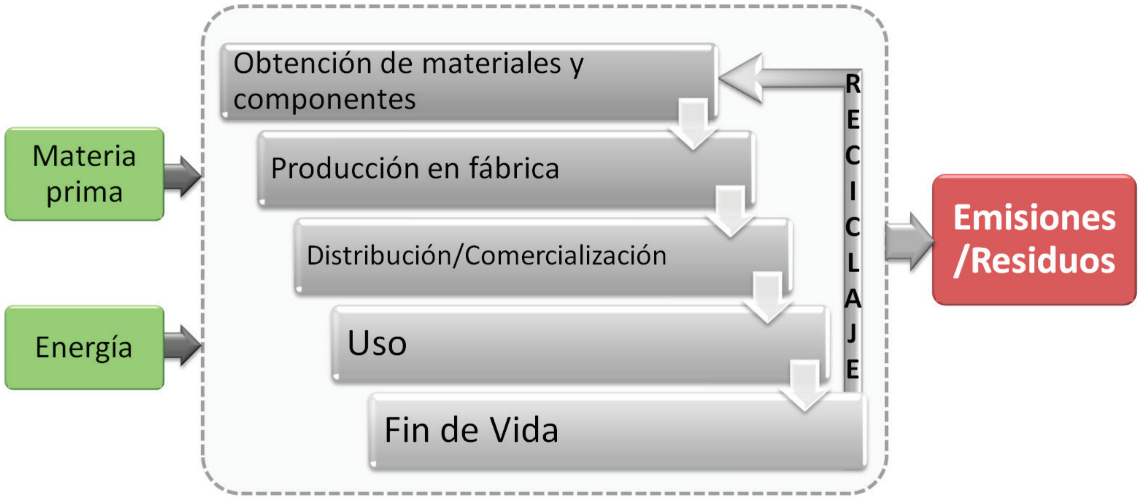

FIGURA 2: DEFINICIÓN DEL CICLO DE VIDA DE UN PRODUCTO, [20]

La aplicación de la metodología de ACV permite analizar productos y procesos muy diferentes, pudiendo encontrar publicaciones en la literatura relativas a productos como una placa de inducción, [21], [22], procesos de tratamiento de agua [23], evaluación de impacto de aerogeneradores, [24], [25], invernaderos, [26], maquinaria agrícola, [27], contenedores, [28], luminarias, [29], pilas combustible, [30], el sector del vino, [31], envases de bebidas, [32], muebles, [33], producción de alimentos como el queso, [34],...etc. El objetivo del estudio es identificar los elementos que generan los impactos ambientales más relevantes con el fin de identificar cuáles pueden ser optimizados en búsqueda de la reducción de ese impacto.

El tercer paso en la realización de un ACV ha de realizarse haciendo uso de una metodología de cálculo. Existen dos maneras diferenciadas de evaluación del impacto ambiental: metodología midpoint y endpoint. En las metodologías midpoint se evalúa de forma separada cada categoría de impacto. La segunda alternativa, endpoint, nos devuelve un único valor, resultado de la ponderación de varias categorías de impacto. Este hecho facilita en gran medida la interpretación de resultados y aunque se considera más subjetivo en la literatura, su uso es recomendado cuando se requiere un resultado final, [35].

Para el desarrollo de esta tesis doctoral se ha utilizado ReCiPe, una metodología endpoint, que proporciona resultados ponderados en mPt, pero que a su vez permite disponer del desglose de las 18 categorías de impacto de las que se nutre, [36], [37].

Otra de las metodologías utilizadas en este trabajo, referencia en el ámbito científico, es la metodología midpoint CML, con 11 categorías, [38], [39]. Concretamente, se hace uso de la categoría Global Warming Potential, cuya unidad son los kg de CO_2 equivalentes. En esta categoría se evalúa la influencia que el objeto de análisis posee sobre el cambio climático a 100 años.

Para aplicar la metodología del ACV resulta esencial contar con softwares específicos. Uno de los más prestigiosos actualmente es SimaPro, con el cual se pueden realizar ACVs de productos de gran complejidad, mediante la estructura que proporciona el programa. A su vez dentro de este software se integran bases de datos como EcoInvent v3.01, punto de partida de esta investigación, [40], [41].

La base de datos para la evaluación del impacto ambiental, EcoInvent, contiene más de diez mil datasets tanto de materiales como procesos, siendo una de las más utilizadas en este campo de investigación, [42].

El dataset dedicado al proceso de inyección de plásticos se basa en el informe [43]. En éste se recogen las entradas y salidas del procesado de tres termoplásticos diferentes, en distintas fábricas, concretamente el policloruro de vinilo (PVC), el polipropileno (PP), y el tereftalato de polietileno (PET), [44], [45]. Los datos finales de EcoInvent se obtienen de la media de los valores de estos informes, aun habiendo diferencias notables entre los tres plásticos, o no contando en alguno de los tres casos como valores registrados (donde se consideraron cero antes de realizar la medida aritmética). Este inventario generado en el informe se correlaciona con datasets ya definidos por EcoInvent. Es decir, de forma pormenorizada, cada dataset es un ACV en sí mismo.

De esta manera, dentro del dataset para la obtención de un kilogramo de plástico inyectado, se recogen entradas de materiales como aceites lubricantes, aditivos (que requiere el procesado del PVC, [46]), agua consumida, embalaje donde se contemplan materiales como cartón, pallets, films plásticos, así como entradas de energía en forma de electricidad, gas natural u otros combustibles (Tabla 1). Por otro lado, se presentan como salidas de este proceso residuos, que o bien son enviados a vertedero, incinerados o tratados como peligrosos, y emisiones al agua y al aire (también incluidas en gran parte por el caso especial del PVC).

La recogida de datos experimentales a nivel de máquina o proceso resulta difícil en muchas ocasiones, donde sólo se dispone de valores a nivel de fábrica, de forma agregada. La iniciativa CO2PE! trata de abordar este tema analizando los problemas que se dan en este aspecto en las siguientes investigaciones, [47], [48], [49], [50], [51].

Nombre	EcoInvent 3	ReCiPe [mPt]	Kg CO_2 eq.
Agua	Water, cooling, unspecified natural origin	--	--
Aceite, lubricantes	Lubricating oil {GLO}| market for | Alloc Def, U	0,81	3,56E-03
Solventes	Solvent, organic {GLO}| market for | Alloc Def, U	8,49	4,07E-02
Estabilizantes	Chemical, organic {GLO}| market for | Alloc Def, U	3,50	2,68E-02
Pigmentos	Titanium dioxide {RER}| market for | Alloc Def, U	1,24	1,20E-02
Pallets	EUR-flat pallet {GLO}| market for | Alloc Def, U	5,92	1,63E-02
Cartón	Solid bleached board {GLO}| market for | Alloc Def, U	0,05	1,46E-04
LDPE film	Polyethylene, low density, granulate {GLO}| market for | Alloc Def, U	0,48	3,73E-03
PP Strapping	Polypropylene, granulate {GLO}| market for | Alloc Def, U	1,00	7,45E-03
Kaolin	Kaolin {GLO}| market for | Alloc Def, U	0,07	7,49E-04
Talco	Malusil {GLO}| market for | Alloc Def, U	0,002	2,06E-05
Cal	Lime {GLO}| market for | Alloc Def, U	0,04	3,60E-04
Electricidad	Electricity, medium voltage market for | Alloc Def, U	69,08	0,75
Gas natural	Heat, district or industrial, natural gas | market for heat, district or industrial, natural gas | Alloc Def, U	16,33	0,18
Fuel Oil	Heat, district or industrial, other than natural gas| market for heat, district or industrial, other than natural gas | Alloc Def, U	1,83	0,02
Infraestructura	Packaging box factory {GLO}| market for | Alloc Def, U	1,10	8,10E-03
Plástico, a incinerar	Waste plastic, mixture {GLO}| market for | Alloc Def, U	0,66	1,36E-02
Residuo peligroso	Hazardous waste, for underground deposit {GLO}| market for | Alloc Def, U	0,001	9,90E-06
A vertedero	Municipal solid waste {GLO}| market for | Alloc Def, U	0,03	4,57E-04
	Water/m3	--	--
	Water, RER	--	--
SS	Suspended solids, unspecified	--	--
DQO	COD, Chemical Oxygen Demand	--	--
	DOC, Dissolved Organic Carbon	--	--
	TOC, Total Organic Carbon	--	--
	BOD5, Biological Oxygen Demand	--	--
	TOTAL	**111,01**	**1,09**

TABLA 1: DATASET DE ECOINVENT Y RESULTADOS DE IMPACTO AMBIENTAL, [52]

Revisando el estado del arte, concretamente, en el campo de la inyección de plásticos podemos encontrar numerosos estudios de simulación CAE, [53], [54], donde se plantean métodos de optimización para los parámetros del proceso de inyección como el realizado Kitayama y Natsume, en el que buscar minimizar la fuerza de cierre y las contracciones, asegurando el completo llenado. El conseguir una menor fuerza de cierre aumenta la productividad del proceso y a su vez el poder utilizar una máquina más pequeña, repercutirá en el consumo eléctrico del proceso, [55].

La investigación en nuevos sistemas de refrigeración del molde también es de un alto interés, al representar hasta el 80% del tiempo de ciclo del proceso en algunos casos, [56], [57], [58]. La relación entre el consumo eléctrico y las características del proceso es compleja de modelar y no lineal, [59]. Una forma de obtener ahorro de energía es mediante la optimización de los parámetros del proceso y un modelo matemático del consumo energético, otra de las maneras, que supone un mayor coste, es invertir en la mejora de la maquinaria o en nuevos equipos con tecnologías más eficientes, [60], [61]. Packianather et al. plantean un diseño de experimentos para optimizar el proceso sobre una máquina de inyección, [62].

Una primera revisión del proceso de inyección desde el punto de vista ambiental es realizada por Thiriez, incluyendo la producción de los termoplásticos y sus aditivos, además del proceso de inyección en sí, [63]. En este estudio se remarca la importancia que tiene la selección del tipo de máquina inyectora, ya que ésta puede suponer un alto valor de energía específica, y por tanto influenciar en gran medida en el impacto ambiental del proceso, [64]. Cuando los movimientos de la máquina se consiguen únicamente por bombas, la máquina se considera puramente hidráulica. Hoy en día casi ninguna máquina es puramente hidráulica, ya que se emplean mecanismos que ayudan al sistema hidráulico, como puede ser el mecanismo de rodillera. A estas máquinas se les denomina híbridas, [65]. Las máquinas eléctricas reemplazan el circuito hidráulico por servomotores, [66], [67], y permiten obtener ahorros entre el 30 y el 70% debido a una conversión más directa de la energía, [68]. Una de las características que definen una máquina de inyección es la fuerza de cierre. Existen máquinas dentro de un amplio rango de fuerzas de cierre, desde micro inyectoras de menos de 5 toneladas hasta grandes máquinas de 10000 toneladas, [69].

En la tesis de Almeida, se realiza un LCE (Life Cycle Engineering), siguiendo la aproximación de la cuna a la tumba, para determinar el impacto ambiental del proceso de inyección de plásticos biodegradables, analizando a la par los costes de las distintas fases [70]. Por ejemplo, se analizan los escenarios de fin de vida, considerando el compostaje de los residuos, al tratarse de plásticos biodegradables.

En el trabajo realizado por Ribeiro et al. se analizan distintos diseños de molde estudiando cómo se ve influenciado el coste económico de la producción en un ejemplo de una pieza de plástico, [71]. En esta publicación se presentan varios tipos de molde y su coste, destacando los de colada fría como los más económicos, en la mayoría de los casos. Bajo el criterio de mínimo coste, esta opción podría resultar la mejor valorada. No obstante, si se analiza el proceso de forma global, se deben tener en cuenta más factores para tomar la decisión correcta. En caso de optar por la colada fría, el tiempo de ciclo será mayor, influyendo en el consumo requerido y la productividad. Esta opción consume también más materia prima, por lo que se deben tener en cuenta todos los factores intervinientes, a la par.

Esta necesidad de analizar la reducción de impacto ambiental y económico de forma holística, también la refuerzan Lucchetta y Bariani con su estudio de optimización, [72]. En su análisis explican cómo se obvia de forma errónea la repercusión que tiene sobre el proceso de fabricación, ya sea por el aumento de consumo energético o por un aumento de complicación, cambios en el diseño de la pieza, buscando por ejemplo reducir espesores para rebajar el consumo de materia prima, e introduciendo nervios que mantengan las prestaciones estructurales.

Müller et al. plantean una forma alternativa de analizar el consumo eléctrico del proceso de inyección de plásticos, de una forma dual, separando los elementos que aportan valor de los que no, para incrementar la eficiencia de este proceso. A su vez, realizan medidas experimentales muy interesantes, realizando llenados en vacío, con aire, y determinando por diferencias con el consumo del procesado de una pieza, la energía requerida para las fases de plastificación y llenado (0,16kWh/kg, en su caso), [73].

El consumo eléctrico del proceso de inyección de plásticos es elegido como indicador de sostenibilidad por parte de Madan et al. dentro de su estudio. Desde el punto de vista de estos investigadores en los ACV de forma general se da mucho más importancia al material que a los procesos de fabricación por lo que plantean una metodología de estimación de consumos eléctricos de los procesos de fabricación, con el objetivo de poder realizar benchmarking, y contar con herramientas de evaluación para buscar acciones de mejora, [74].

Otro punto de vista lo aportan Yam y Mak, estudiando la inyección de plásticos con gas, para obtener reducciones en el uso de polímeros y obteniendo reducciones de energía del 20%, reduciendo parámetros de proceso como la presión de inyección y la fuerza de cierre requerida para la fabricación de una pieza, [75].

Spiering et al. realizaron un benchmark de la eficiencia del proceso de inyección, subrayando el hecho la falta de datos existente en el ámbito de los procesos de fabricación para generar el inventario del ciclo de vida, al contrario que la información en detalle que se tiene en otras fases como en el uso del producto, [76]. Esto provoca que el potencial para reconocer áreas de mejora sea bajo. Uluer et al. proponen la monitorización del consumo eléctrico como un método para analizar relaciones con la fabricación de producto, que permita determinar acciones de mejora, y de este modo reducir el impacto ambiental y económico, [77].

Mejorar la evaluación del impacto ambiental de los procesos de fabricación es objetivo de muchas publicaciones científicas, [78], [79], [49]. En general, existe una alta variación en las demandas de energía de los procesos de fabricación, por lo que es necesario abordar su estudio mediante aproximación teórica o más en detalle realizando medidas experimentales [50].

En la industria del mecanizado se pueden encontrar numerosos estudios acerca del consumo de energía de estos procesos, donde se estudian la influencia de la selección de máquina, o la secuencia de operaciones, [80], los parámetros de operación óptimos, [81], el perfil de demanda de energía de la máquina en el proceso, [82], formas de monitorizar el consumo de energía, [83], o estimarla, realizando medidas experimentales para su validación, [84], tomando, como en el estudio de Kara y Li, el valor de SEC (Specific Energy Consumption, kWh/kg) como referencia para establecer comparaciones entre procesos, [85].

Abeykoon et al. estudiaron la demanda eléctrica en la extrusión de polímeros, alterando condiciones del proceso para mejorar su eficiencia, [86]. A mayores valores de kg/h, la demanda se veía reducida, [87]. Deng et al. presentaron un método de monitorización del consumo eléctrico a tiempo real para analizar la calidad del fundido del material y la demanda eléctrica en función de los parámetros del proceso de extrusión, [88].

La implementación de metodologías Lean, como las 5S, se plantean como forma para reducir los impactos en la producción, al mejorar la gestión de residuos o los layout en planta, que mejoran la eficiencia de los procesos, [89], [90]. A su vez, varios autores plantean la idea de incluir el criterio de eficiencia energética en la programación de sistemas de producción mediante la estimación de consumo de energía a nivel de máquina, [91]. Además el coste de producción podría optimizarse haciendo uso de la variación del precio de la electricidad, en función de la hora de uso, [92].

Tras haber realizado un análisis detallado del Estado del arte se puede resaltar la gran importancia que tiene el análisis del impacto ambiental, especialmente en la última década. Centrándonos en el análisis del proceso de inyección, la comparativa entre artículos ha permitido ver la gran variabilidad de resultados posibles y la relevancia que tiene el consumo eléctrico en este proceso tanto en el impacto ambiental como económico.

2.1. SÍNTESIS, JUSTIFICACIÓN Y APORTACIONES

Tal y como se puede extraer del estudio del estado del arte, la investigación en el impacto ambiental de cualquier producto o proceso es de gran interés debido a la actual situación social y medioambiental, por lo que profundizar en el estudio detallado de un proceso como el de la inyección de plásticos, o realizar un análisis de ciclo de vida de una pieza supone un tema relevante para las publicaciones científicas.

El interés de este estudio reside en que el resultado de la investigación tiene un alto nivel de aplicabilidad. Analizar la sostenibilidad medioambiental y económica de una pieza de inyección de plástico cuyo proceso es tan extendido y desarrollar una herramienta para su cálculo y optimización, puede suponer una ventaja competitiva dentro del sector para las posibles empresas que la apliquen, permitiendo la optimización de la producción, los elementos que en ella intervienen y sus procedimientos de gestión. Tras la realización de esta investigación se ha desarrollado una metodología de trabajo novedosa con información detallada, que será útil para complementar los criterios de selección de máquina, diseño de utillajes, gestión de materiales y residuos. En definitiva, facilita la toma de decisiones en el desarrollo de un componente considerando factores tan importantes como el económico y el ambiental, que son imprescindibles en procesos de fabricación a gran escala.

La aportación de la investigación al ámbito del Análisis de Ciclo de Vida también puede resultar de gran interés para este campo al presentarse metodologías alternativas de evaluación que mejoran los resultados de impacto ambiental, aportando mayor sensibilidad.

Capítulo 3

Análisis de Ciclo de Vida

3. ANÁLISIS DE CICLO DE VIDA

En este capítulo se muestran las distintas etapas del ciclo de vida de una pieza de plástico inyectada. Dentro de cada fase se propone una metodología de cálculo para la evaluación tanto del impacto ambiental como del coste económico.

Los apartados en los que se ha dividido el ciclo son los siguientes:

- Producción de la materia prima
- Distribución de la materia prima
- Proceso de Inyección de Plásticos
- Post procesado
- Embalaje
- Distribución a cliente
- Fin de vida

3.1 PRODUCCIÓN DE LA MATERIA PRIMA

Dentro de esta fase se plantea incorporar el porcentaje de composición de la materia prima, realizando, si fuera necesario, una ponderación entre el termoplástico y sus cargas y/o aditivos que permiten modificar sus propiedades tanto mecánicas, eléctricas o térmicas, como los retardantes de llama, o aquellos aditivos que influyen en el aspecto estético del material, como el color.

Además, dentro de la metodología de cálculo que se muestra en la Figura 3, se incluye la opción de incluir elementos, dentro de la materia prima, como pueden ser insertos metálicos que se añaden a la pieza inyectada.

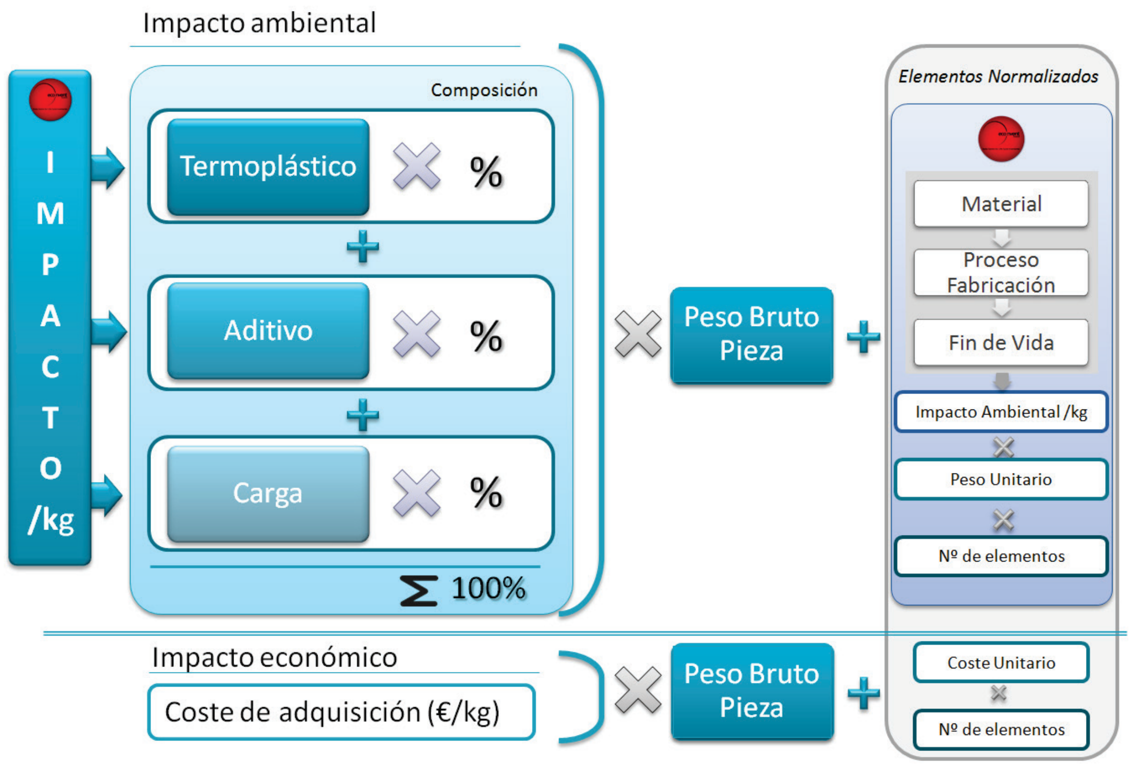

FIGURA 3: CÁLCULO EN LA PRODUCCIÓN DE LA MATERIA PRIMA, [20]

3.2 DISTRIBUCIÓN DE LA MATERIA PRIMA

La siguiente fase a la producción de la materia prima en el ciclo de vida de una pieza plástico es la distribución de ésta a las plantas de procesado (Figura 4).

El coste de esta fase se considera cero, al asociarse dentro del propio precio de adquisición incluido en la primera fase del ACV.

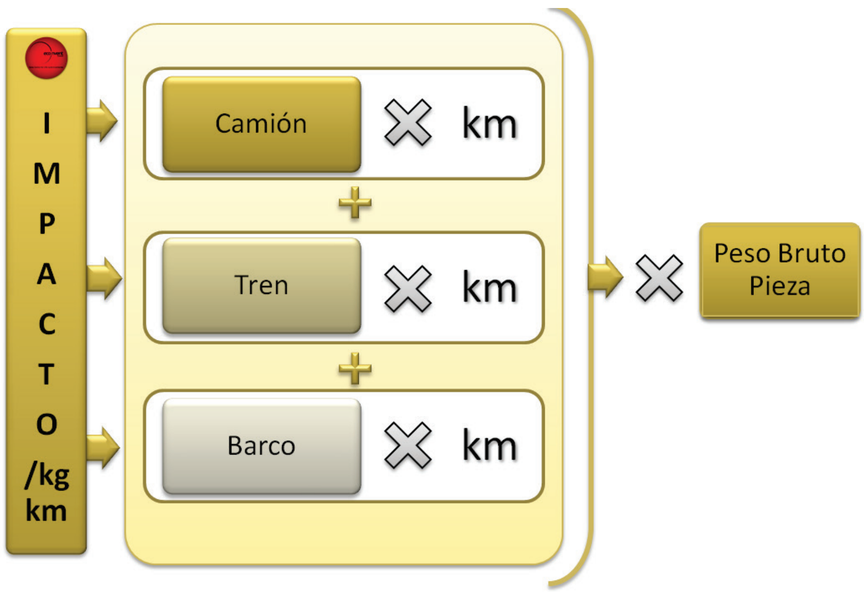

FIGURA 4: CÁLCULO EN LA DISTRIBUCIÓN DE LA MATERIA PRIMA, [20]

Si es preciso analizar con mayor nivel de detalle esta fase, debería incluirse el embalaje de los pellets, ya sea en forma de caja o saco, e incluir la posibilidad de reutilización. Esto se ha implementado dentro de la aplicación informática que se mostrará al final de este capítulo.

3.3 PROCESO DE INYECCIÓN

Para el ACV específico del proceso de fabricación, se planteó en un primer paso una aproximación teórica recogida en el siguiente apartado.

3.3.1 METODOLOGÍA 1

Para el desarrollo de esta metodología se realizó una revisión del proceso de inyección de plásticos con el objetivo de identificar todos los elementos implicados.

En un primer paso, los pellets de plástico son introducidos en la tolva de la máquina de inyección para su fundición dentro de la cámara de plastificación. El ciclo comienza tras el cierre del molde. La dosis se inyecta en la fase de llenado, completándose en la fase de compactación. Una vez finalizados estos procesos comienza la refrigeración que permite reducir la temperatura del molde para la expulsión adecuada de la pieza. A su vez, el husillo en la unidad de inyección rota para volver a la posición anterior y preparar una nueva dosis.

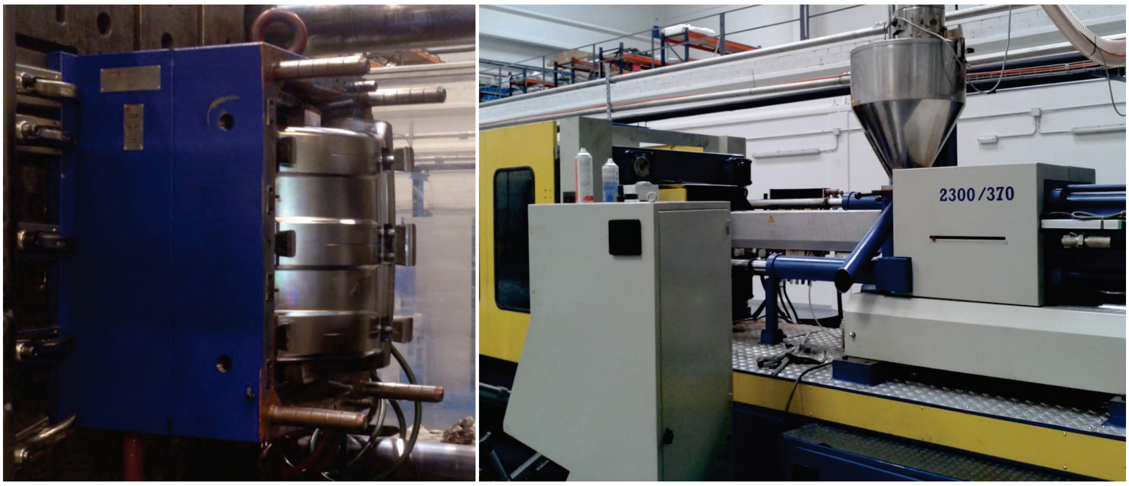

FIGURA 5: MOLDE Y MÁQUINA DE INYECCIÓN

Previos al proceso, equipos como alimentadores o los secadores, pueden ser necesarios para preparar el material. Los materiales higroscópicos, como las poliamidas, que absorben humedad, requieren de este proceso previo, para evitar que aparezcan defectos en la pieza.

Para el cálculo en esta fase, es necesario distinguir el peso bruto y neto de la pieza. Esta diferenciación viene dada por el diseño del molde:

- Sistema de alimentación
    - Cámara caliente (hot runner)
    - Colada fría (cold runner)
- Número de cavidades del molde

Los sistemas de cámara caliente, mantienen los canales de alimentación del molde fundidos, permitiendo expulsar la pieza sin coladas. Aunque suponen una inversión inicial más elevada, incrementan la productividad, al reducirse el tiempo de ciclo y permiten un ahorro de material.

De este modo, si estamos ante una pieza mono cavidad con cámara caliente, el peso bruto inyectado y el neto final de la pieza serán equivalentes.

Tras el estudio, se identifican tres grandes bloques a evaluar en el proceso:

- Consumo eléctrico
- Maquinaria y Molde
- Mantenimiento

Los kWh/kg procesados se pueden estimar como suma de los bloques mostrados en la Figura 6. Para el cálculo del impacto o del coste se habrá de seleccionar el mix eléctrico correspondiente al lugar de fabricación de la pieza, o los /kWh consumidos.

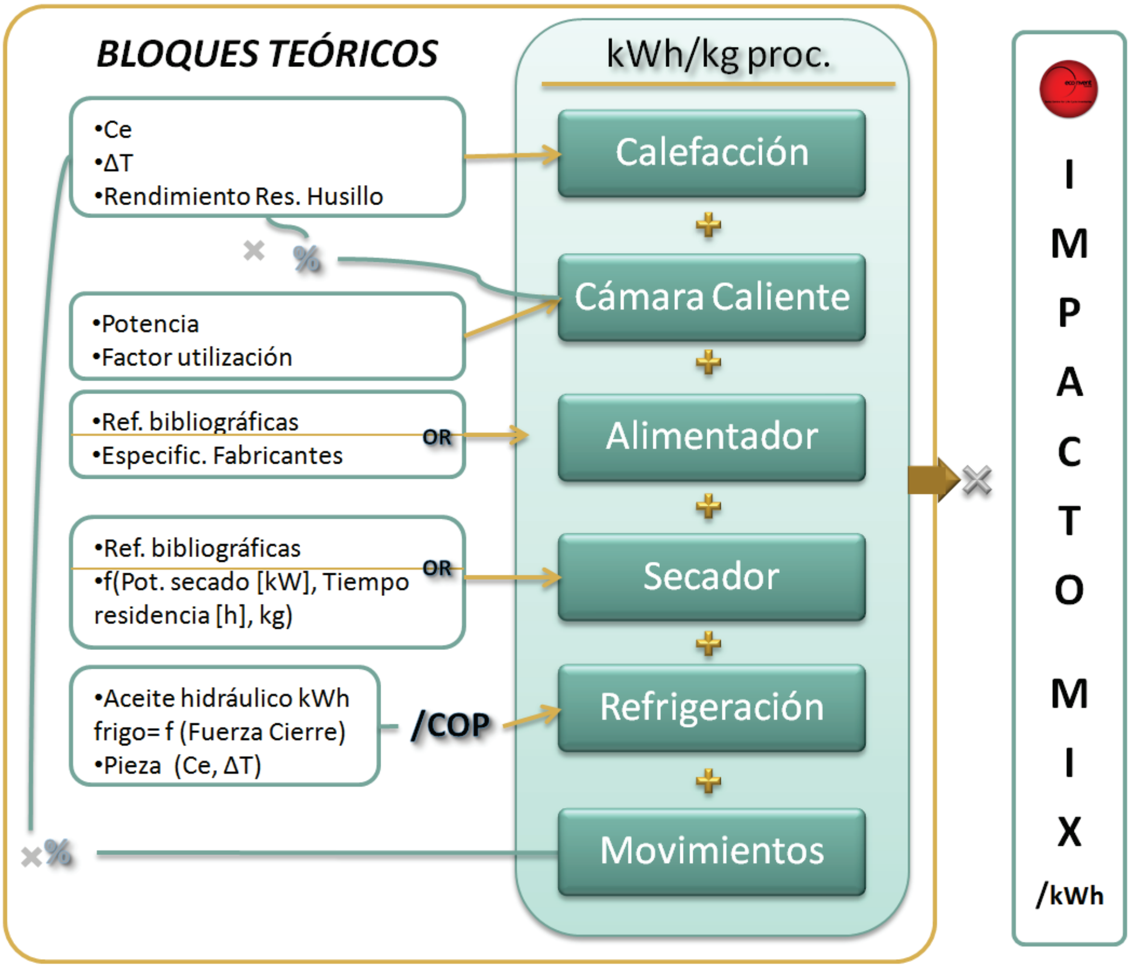

FIGURA 6: APROXIMACIÓN TEÓRICA DEL CÁLCULO DEL CONSUMO ELÉCTRICO DEL PROCESO, [20]

Los materiales empleados en la fabricación de la maquinaria y molde se consideran en el siguiente bloque a evaluar.

El impacto ambiental de los metales se habrá de repartir entre todos los kilogramos que se procesen en su vida útil.

De igual modo se procede con el coste económico, aunque en este caso se debe considerar el coste de los operarios.

La Figura 7 resume de forma esquemática la forma de cálculo.

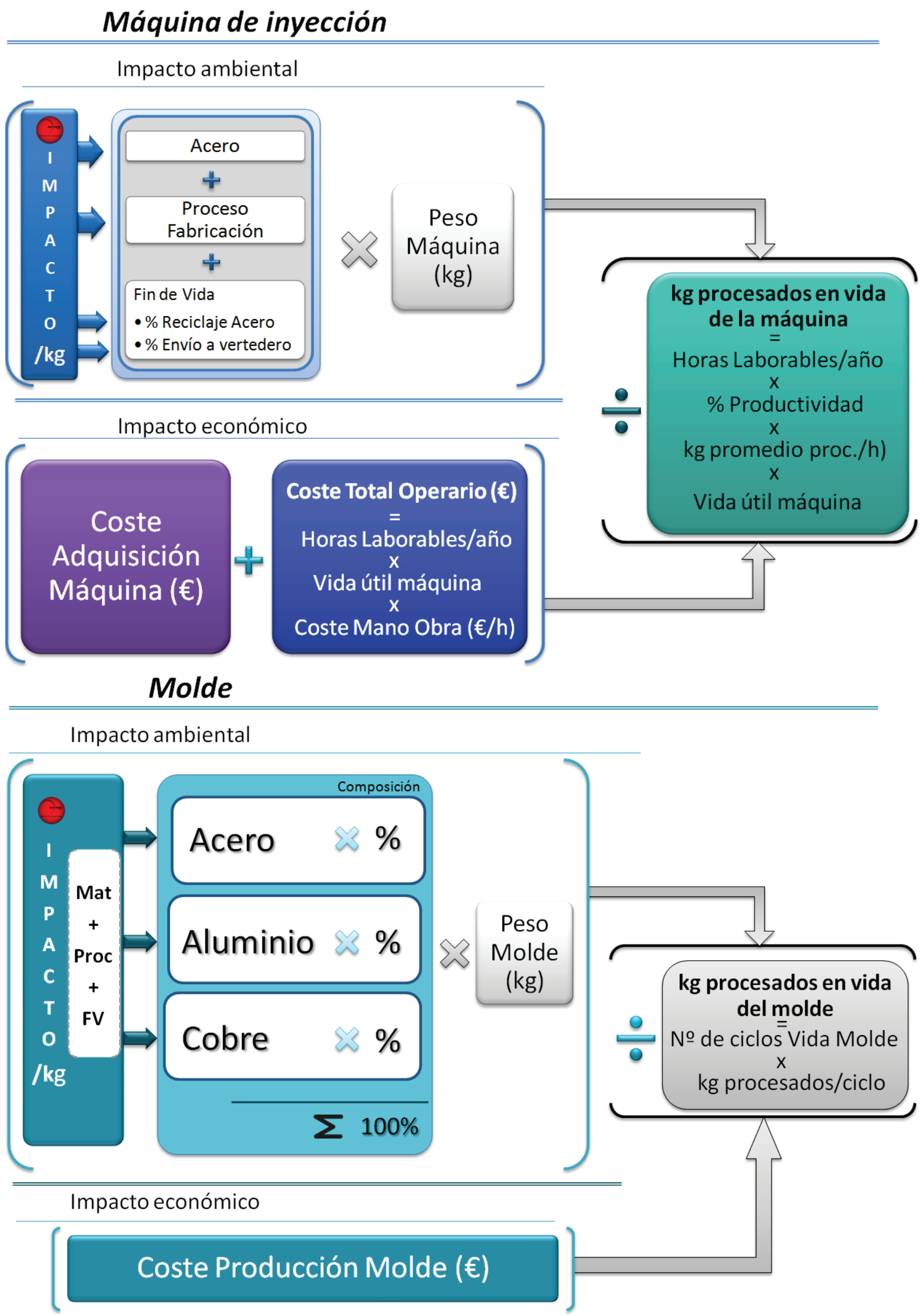

FIGURA 7: METODOLOGÍA DE CÁLCULO PARA EVALUAR LA MÁQUINA Y EL MOLDE DEL PROCESO DE INYECCIÓN, [20]

Por último se evalúa el mantenimiento requerido por la máquina de inyección, incluyendo el impacto que supone el aceite hidráulico empleado y su tratamiento de fin de vida en los recambios que se realicen (Figura 8).

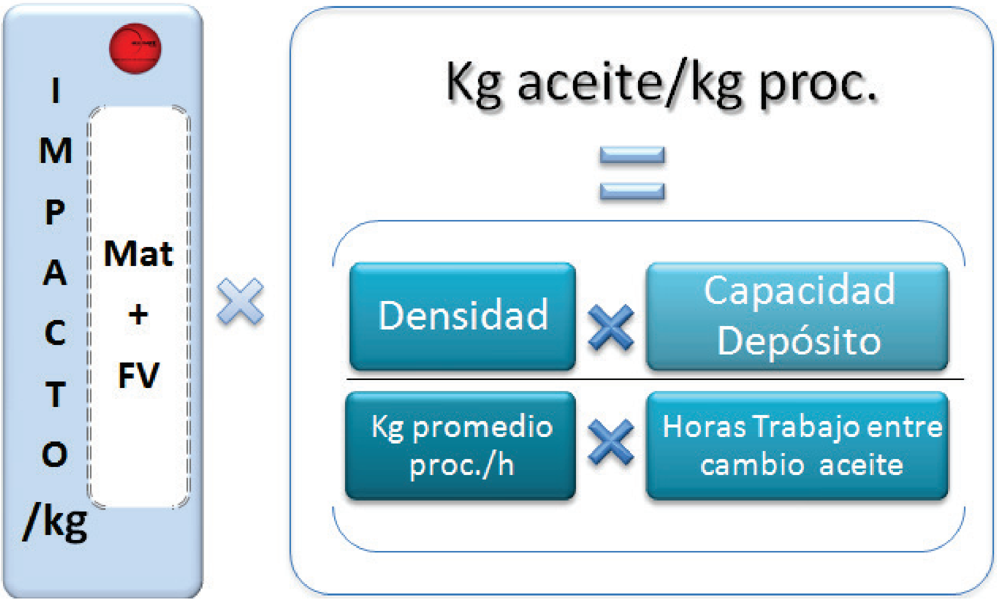

FIGURA 8: METODOLOGÍA DE CÁLCULO PARA EL MANTENIMIENTO DE LA MAQUINARIA, [20]

Para completar el cálculo del proceso de inyección se emplean un total de unos 30 parámetros relacionados con la pieza, máquina y molde utilizados.

1. Peso neto de la pieza
2. Tipo de sistema de alimentación
3. Número de cavidades del molde
4. Material
5. Calor específico del material
6. Rendimiento del husillo
7. Temperatura de inyección
8. Temperatura de la fabrica
9. Potencia de la Cámara Caliente (Factor de utilización)
10. Fuerza de cierre de la máquina de inyección
11. Potencia del equipo Alimentador (seleccionando modo de trabajo)
12. Potencia del Secador (Horas de trabajo)
13. Coeficiente COP del sistema de refrigeración
14. Temperatura de expulsión
15. % Movimientos frente a % Plastificación
16. Mix eléctrico a utilizar (país de fabricación)
17. Peso de la Máquina de Inyección
18. % Fin de vida de la Máquina
19. Peso del Molde
20. Composición del Molde
21. % Fin de vida del Molde
22. Ciclos realizados en vida de molde
23. Horas por turno
24. Número de turnos
25. Días laborables al año
26. Productividad
27. Vida útil de la máquina de inyección
28. Densidad del aceite hidráulico
29. Capacidad depósito aceite
30. Horas de trabajo entre cambio de aceite

3.3.2 Metodología 2

Dada la importancia del consumo eléctrico en el resultado total del impacto ambiental, se plantea la siguiente metodología como alternativa de cálculo rápida y precisa de la evaluación del proceso (Figura 9).

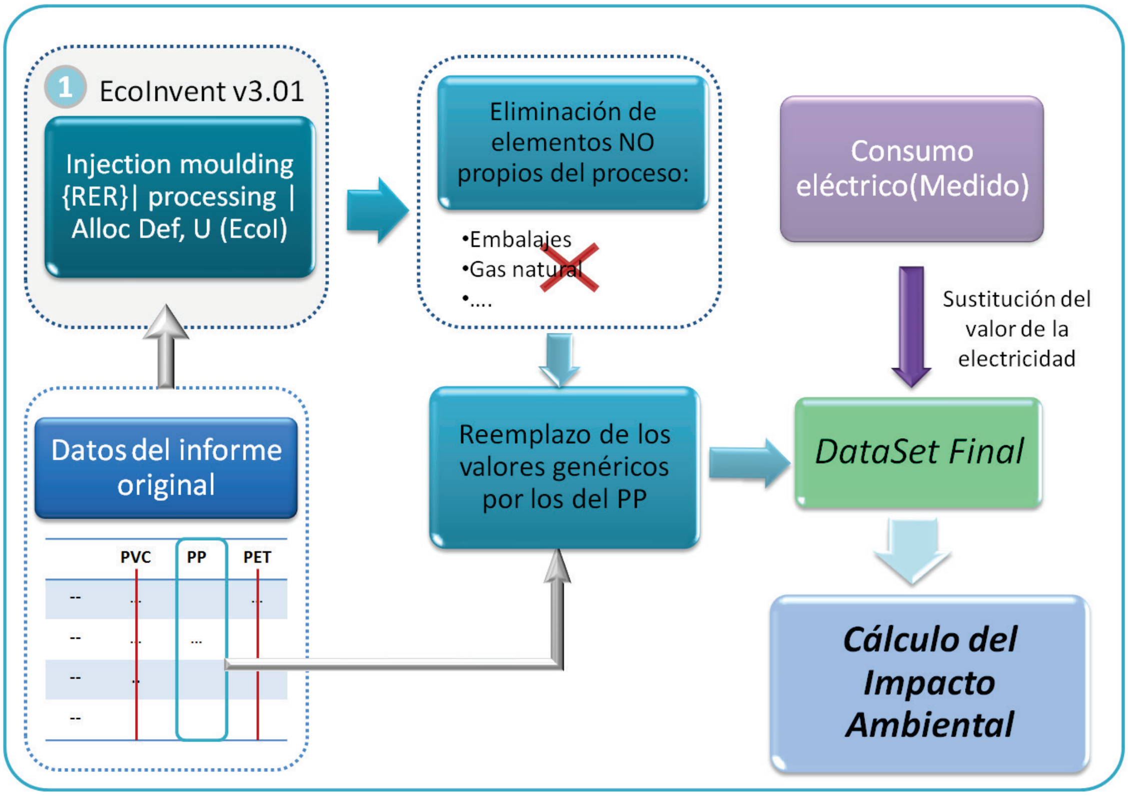

FIGURA 9: METODOLOGÍA 1, PARA EL PROCESO DE INYECCIÓN DE PLÁSTICOS, [52]

En la Figura 9 se muestra el proceso de creación del dataset para la evaluación del impacto ambiental. Se parte del dataset de la base de datos EcoInvent, la cual se nutre del valor promedio de tres plásticos: PVC, PP, y PET. En este dataset se sustituyen los valores promedios por los del termoplástico más convencional, el polipropileno, y a la vez se eliminan elementos que no son propios del proceso, para evitar contarlos doblemente. Por último, para obtener el dataset final se sustituye el valor del consumo eléctrico del PP (2,096 kWh/kg), por el consumo real, medido experimentalmente.

3.4 Post procesado

Tras el proceso de inyección, la pieza está en su forma final. En esta sección permite incluir procesos de acabado que pueda necesitar la pieza, ya sean procesos que requieran algún consumo eléctrico adicional, o materiales extra, de acabado como pinturas o colocación de elementos, como, por ejemplo, una junta...etc.

Hay que tener en cuenta que según los post procesos que se incluyan a la pieza, éstos pueden afectar a las alternativas de fin de vida, provocando, por ejemplo, que no sea posible el reciclaje de la pieza si ésta ha sido pintada.

3.5 EMBALAJE

Dentro del embalaje para el transporte de la pieza al cliente final se han considerado los materiales que se muestran en la Figura 10, planteándose la opción de reutilización.

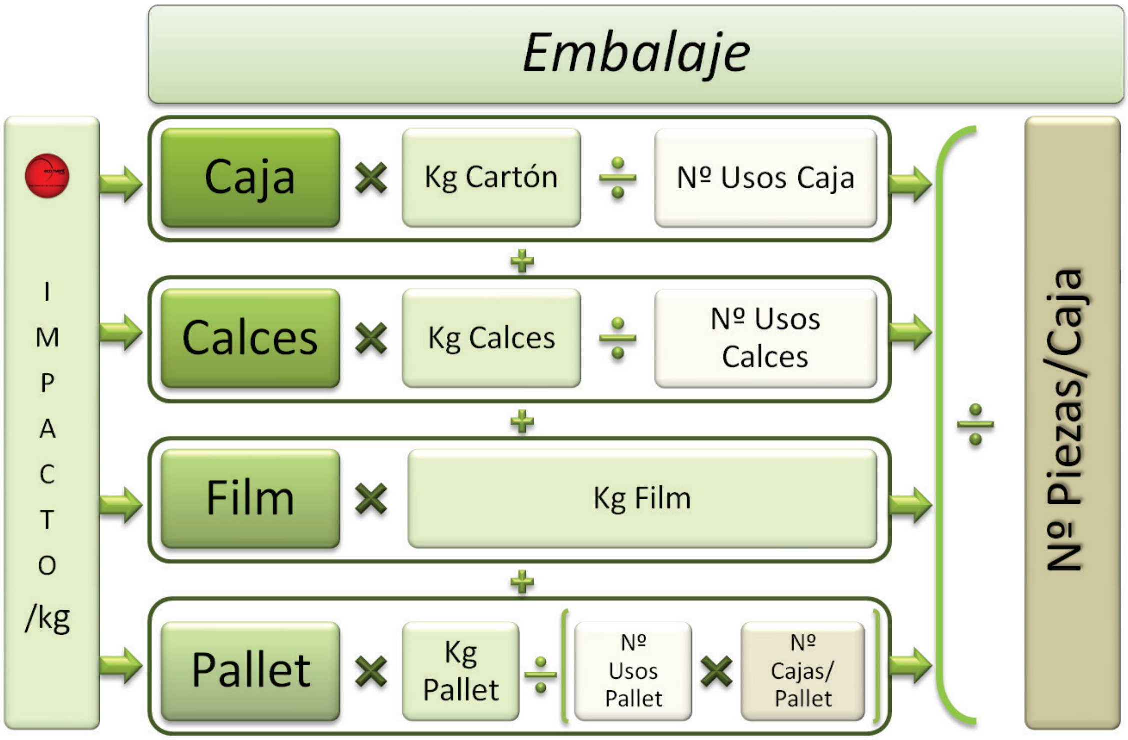

FIGURA 10: METODOLOGÍA DE CÁLCULO PARA EL EMBALAJE, [20]

En este apartado se definen para las últimas dos etapas, dos pesos diferentes, el peso correspondiente para el transporte de una sola pieza, y el peso del embalaje para su tratamiento en el escenario de fin de vida.

3.6 DISTRIBUCIÓN A CLIENTE

En esta fase se sigue el mismo procedimiento que en la etapa de distribución de la materia prima. En este caso el peso a transportar será el peso neto de la pieza, sumado al peso de los elementos, si los hubiera, y el embalaje. Por otro lado, sí se contempla el coste del transporte, haciendo uso de los valores proporcionados en el informe COMPASS de la Comisión Europea, [93], el cual compara los costes (€/ton.km) del transporte en camión, tren y barco.

3.7 FIN DE VIDA

Tras el tratamiento de fin de vida se plantean, para el peso neto de la pieza, el peso de la colada si la hubiera, y el del embalaje, estos tres escenarios:

- Reciclaje
- Envío a vertedero
- Valorización energética

La alternativa de reciclado de plástico es medioambientalmente más beneficiosa que el envío a vertedero o la producción con material virgen, [94]. El informe IEC TR62635, [95], proporciona porcentajes de reciclaje como referencia para distintos tipos de materiales. El escenario de fin de vida de los materiales de embalaje se basa en los datos proporcionados por Eurostat, donde existe información desglosada por país, [96]. Como muestra la Figura 11, la colada puede tratarse según normativa como el resto de la pieza o considerar su trituración, para incorporarla de nuevo a la producción, ahorrando materia prima y reduciendo el impacto.

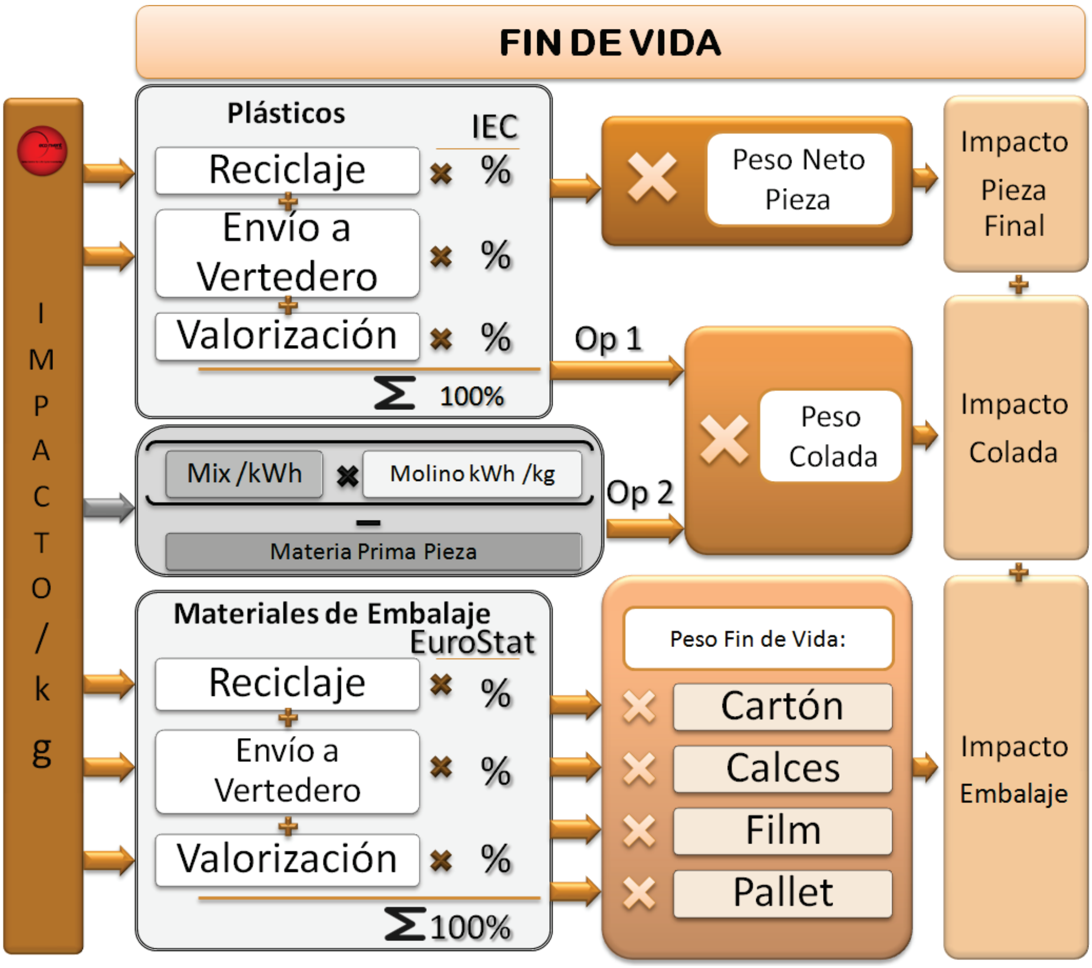

FIGURA 11: METODOLOGÍA DE CÁLCULO PARA LA ETAPA DE FIN DE VIDA, [20]

3.8. APLICACIÓN INFORMÁTICA

La metodología de cálculo propuesta ha sido implementada en una herramienta informática programada con Visual Basic .NET, con el objetivo de obtener resultados de forma sencilla, y poder analizarlos de forma rápida, obteniendo valores de forma desglosada.

La herramienta proporciona resultados de impacto ambiental utilizando la metodología ReCiPe (mPt) y la huella de carbono (kg de CO_2 eq.), así como el coste económico en euros, €.

En la Figura 12, se muestra su pantalla de inicio, desde la cual hay acceso a una guía de usuario. Ésta se puede consultar en el CD adjunto, donde se detalla el funcionamiento y diseño de la aplicación.

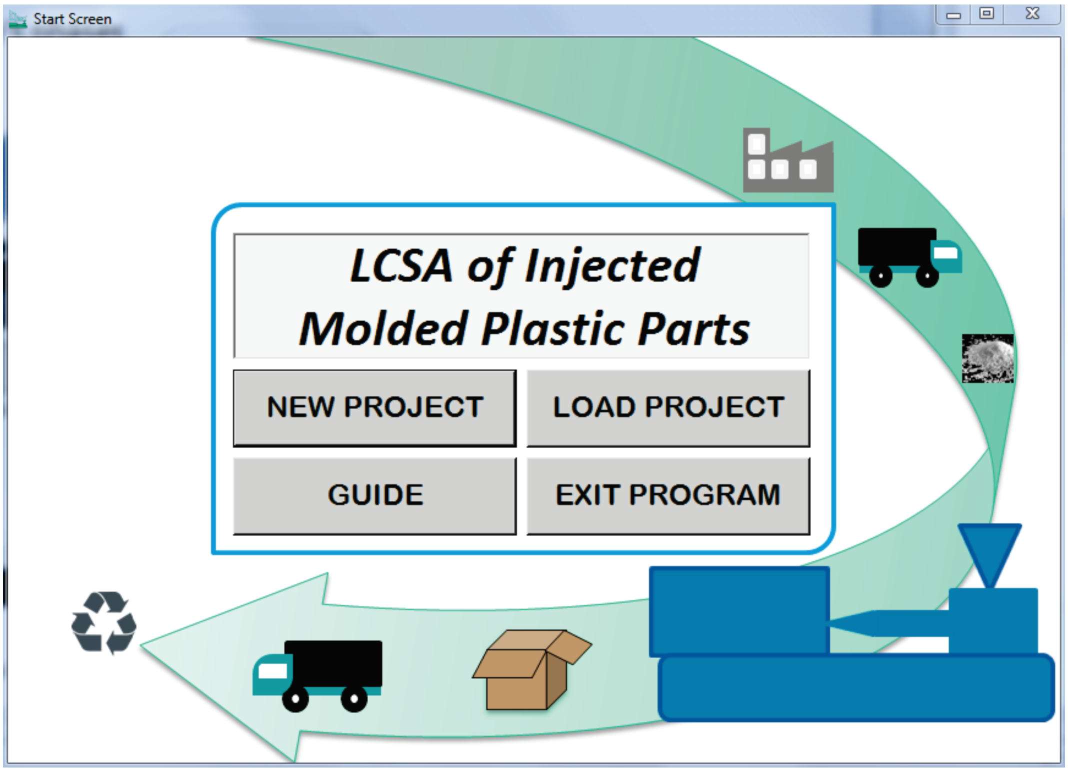

FIGURA 12: PANTALLA DE INICIO DE LA APLICACIÓN INFORMÁTICA

La siguiente imagen muestra una perspectiva de las pantallas a las que se accede desde la pantalla inicial del ACV (Figura 13).

Para facilitar el manejo de la herramienta, además de la una guía de usuario, se incorporan ayudas dentro de cada fase del ciclo.

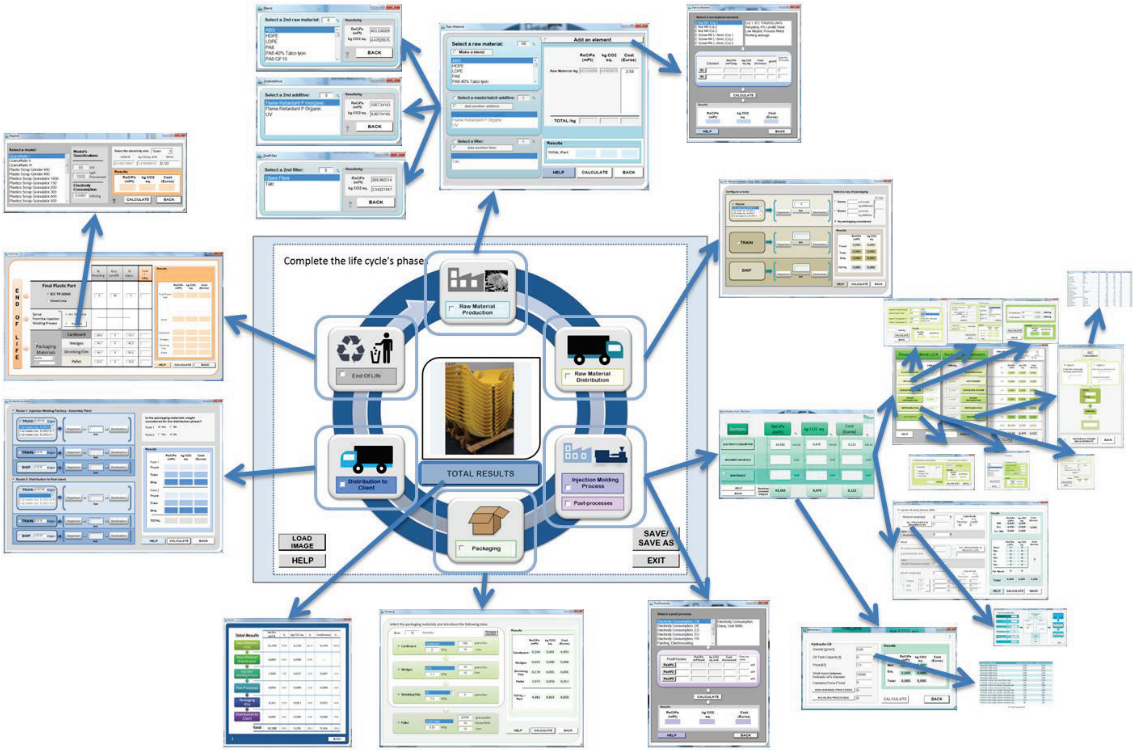

FIGURA 13: PANTALLAS DE LA APLICACIÓN INFORMÁTICA, [20]

El programa se alimenta de bases de datos de elaboración propia, donde se recogen los valores de impacto ambiental calculados con SimaPro y los costes de la materia prima, transportes, embalaje, electricidad, escenarios de fin de vida. Así como propiedades de los plásticos, o ayudas donde figuran especificaciones de equipos...etc. que proporcionan ayuda al usuario a la hora de introducir los datos necesarios para el cálculo.

Dentro de cada apartado se muestran los resultados parciales y en la pantalla principal se desglosan todas las fases incluyendo la importancia en el resultado de cada una de ellas.

Capítulo 4

MEDIDAS EXPERIMENTALES

4. MEDIDAS EXPERIMENTALES

En el siguiente apartado se presenta el equipo utilizado para la realizar las medidas experimentales, así como el procedimiento a seguir. A continuación, se muestran parte de las medidas realizadas, indicando los materiales termoplásticos y las máquinas de inyección utilizadas. Por último, se presentan y analizan los resultados.

4.1. EQUIPO DE MEDICIÓN

Para determinar el procedimiento adecuado de medición y el equipo adecuado fue necesario realizar pruebas, con las que se pudo marcar una pauta a aplicar a todas las mediciones mostradas en este documento.

El equipo de medición de consumo eléctrico, seleccionado para las mediciones, consta de un analizador de redes (Circutor C-80) junto con sus accesorios: pinzas amperimétricas y cables de voltaje (Figura 15). Por otro lado son necesarios guantes de goma para garantizar la seguridad en la conexión del cableado al cuadro eléctrico de la máquina (Figura 16).

Mediante el analizador de redes se registra la potencia consumida en el periodo de muestreo (Figura 14).

FIGURA 14: ANALIZADOR DE REDES, CIRCUTOR C-80

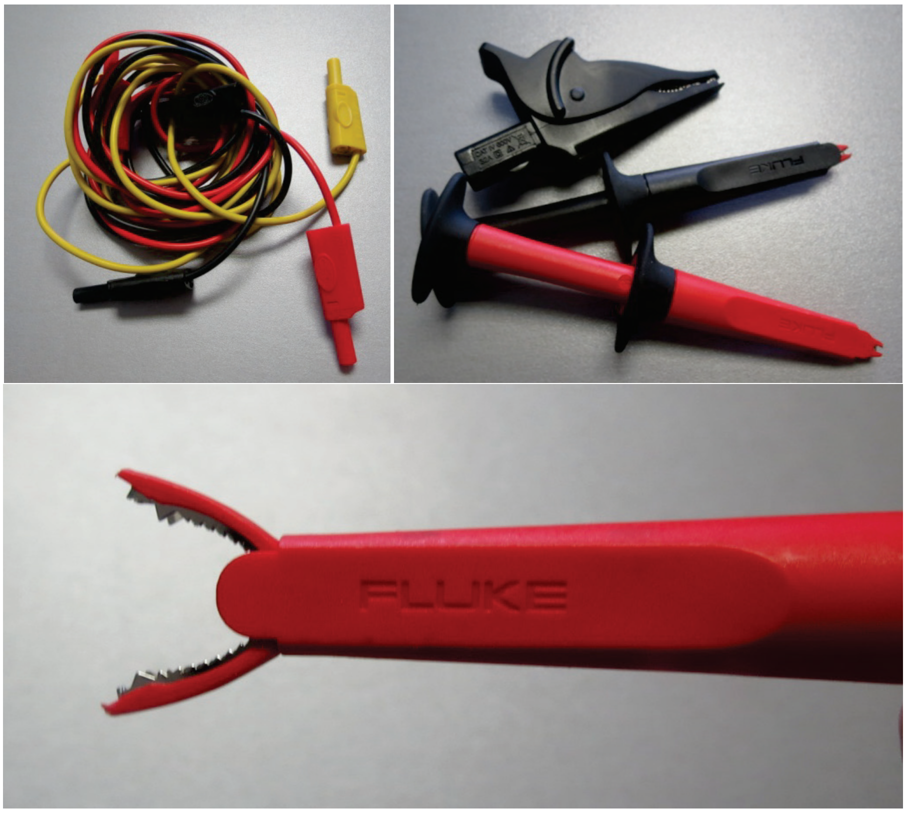

FIGURA 15: CABLES DE VOLTAJE Y PINZAS DE COCODRILO

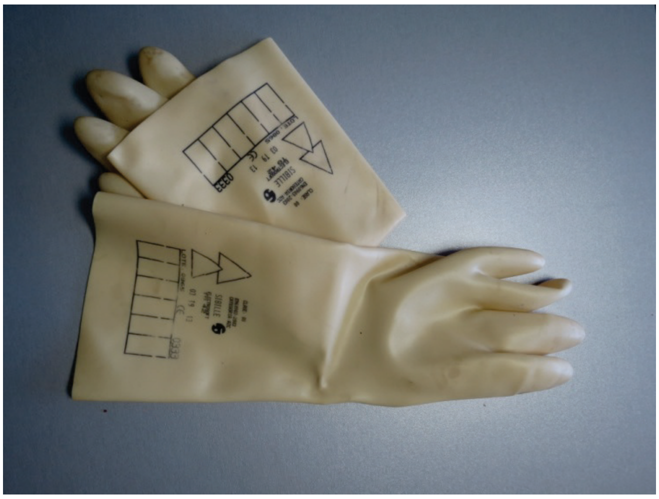

FIGURA 16: GUANTES DE SEGURIDAD

Para la realización de las medidas, hay que tener en cuenta los siguientes puntos:

- Producción estable: deben evitarse puestas en marcha de la máquina, por lo que se recomienda comenzar la medición tras dos horas de producción.
- Tiempo de muestreo del equipo de medición: éste debe englobar varios ciclos de inyección. Típicamente un valor de 10 minutos suele abarcar todo tipo de medidas.
- Pinza amperimétrica adecuada para la medición (Figura 17): se debe asegurar que los picos máximos de intensidad registrados no excedan el

rango de la pinza seleccionada. Para ello se cuenta con tres pinzas que cubren tres rangos de intensidad, hasta 100 A, 500 A y 10000 A. Se debe chequear la máxima intensidad instantánea con el analizador de redes, con el fin de determinar la pinza adecuada. A su vez, el proveedor del equipo aconseja medir en la parte alta de la escala, para mayor precisión, [97] [98].

FIGURA 17: PINZAS AMPERIMÉTRICAS: CP-100, CPR-500, C-FLEX A-45

Teniendo en cuenta los anteriores puntos, tras cada medición se realiza un procesado de los datos, en una hoja de cálculo, verificando la obtención de valores estables, y descartando aquellos fuera del promedio, si hubiera habido algún parón en el proceso.

Con un periodo de muestreo típico de diez minutos, la duración de las mediciones se fija entre dos y tres horas para tener un número relevante de datos con el que determinar si la medición es correcta. Si fuera necesario se repitirá la prueba.

Tras el procesado de los datos, se obtiene el valor promedio de potencia registrado y se calcula el consumo específico por pieza, denominado como SEC, cuyas unidades son kWh/Kg. Para ello es necesario el uso de una balanza con la que registrar el peso bruto inyectado de la pieza y un cronómetro para controlar el tiempo de ciclo.

En la siguiente imagen se muestra el equipo conectado al panel eléctrico durante una medición (Figura 18).

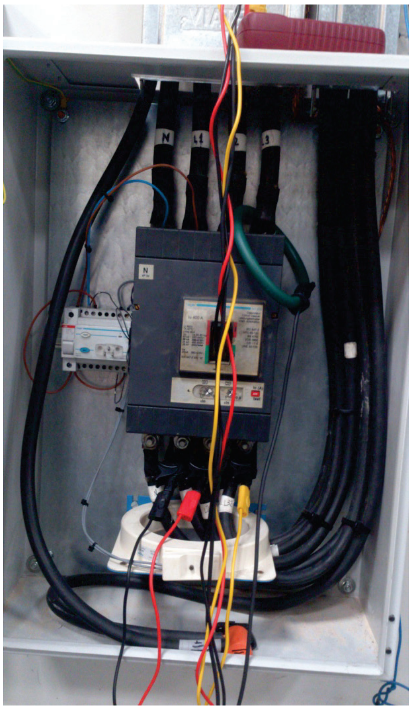

FIGURA 18: EQUIPO CONECTADO AL PANEL ELÉCTRICO

4.2. MEDIDAS

En las medidas experimentales se ha registrado el procesado de los siguientes termoplásticos:

- ABS
- HDPE
- PA
- PA con fibra de vidrio
- PC
- PMMA (10% r)
- SAN
- POM
- PP
- PP (100% r)
- PP + EDPM + talco

Estas piezas han sido inyectadas en tres plantas distintas: aiTIIP, Zalux y CONTENUR en un total de doce máquinas de inyección diferentes, cuyos datos se muestran en la Tabla 2 .

Máquina de Inyección	Fuerza de Cierre (Ton)	Tecnología	Año
A	8000	Híbrida	2005
B	5200	Híbrida	2005
C	3000	Híbrida	2000
D	2000	Híbrida	2010
E	1650	Híbrida	2010
F	1200	Híbrida	1999
G	1000	Híbrida	2008
H	750	Híbrida	2005
I	400	Híbrida	1996
J	200	Híbrida	1999
K	125	Híbrida	1999
L	85	Eléctrica	2002

TABLA 2: MÁQUINAS DE INYECCIÓN MEDIDAS

En las siguiente imágenes se muestran algunas de ellas junto a piezas inyectadas durante las medidas experimentales.

La Figura 19 muestra la máquina de 8000 toneladas de CONTENUR, una de las máquinas de inyección más grandes de España, en la que se tuvo la oportunidad de medir el procesado de un contenedor de 2400 litros de capacidad.

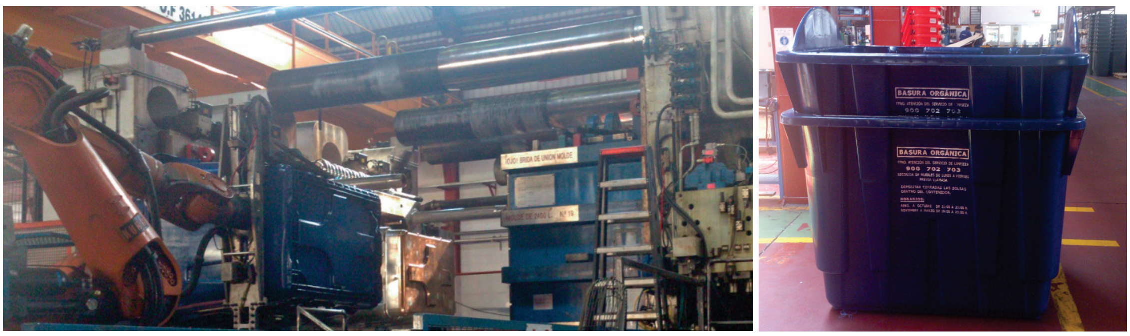

FIGURA 19: MÁQUINA DE INYECCIÓN A, PIEZA 1, CONTENUR

FIGURA 20: MÁQUINA DE INYECCIÓN C, PIEZA 3, AITIIP

FIGURA 21: MÁQUINA DE INYECCIÓN D, PIEZA 10, ZALUX

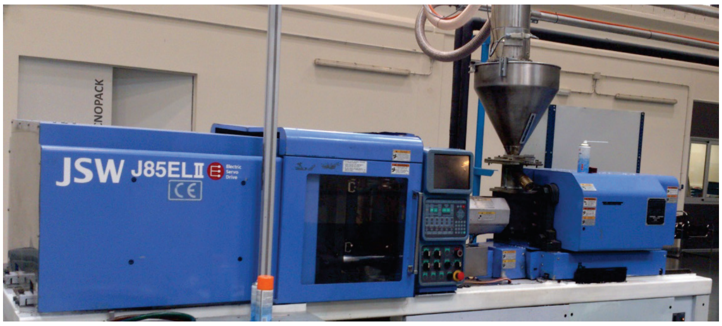

FIGURA 22: MÁQUINA DE INYECCIÓN L, PIEZA 35, AITIIP

En la siguiente tabla se indican algunas de las características de cada pieza inyectada, estos valores serán utilizados, como se verá en el siguiente apartado, para el desarrollo del modelo empírico (Tabla 3).

#	Máq.	Mat.	w[g]	tc [s]	#	Máq.	Mat.	w[g]	tc [s]
1	A	HDPE	71800	216	**19**	H	HDPE	836	40
2	B	HDPE	30300	147	**20**	H	HDPE	1336	162
3	C	HDPE	10500	175	**21**	H	HDPE	260	42,9
4	C	HDPE	8700	194	**22**	I	POM	313 x2 cav	37,6
5	C	PP	7258	140	**23**	I	PP	288 x 2 cav.	84
6	C	PP+EDPM+PE+TD10	4695	118	**24**	I	PA +50% LF	129 x 2cav.	48
7	C	PP+EDPM+10T	3773	108	**25**	I	PA	161	29,2
8	C	PP+EDPM+T15	1802	77,6	**26**	I	HDPE	154 x 2 cav.	47,7
9	C	PP+EDPM+20T	1589	91	**27**	I	HDPE	106	40,3
10	D	PC	646	22	**28**	I	HDPE	100,5 x 8 cav.	44,4
11	E	PC	745	33,7	**29**	J	ABS	39,6	22
12	F	HDPE	2778	139	**30**	K	PA	67,7 x 4 cav.	14
13	F	PP	1560 x 2 cav.	70	**31**	L	PA + 30%GF	68 x 2 cav.	37,2
14	F	HDPE	1253	81	**32**	L	PP (100%-r)	100,47 x 8 cav.	45
15	G	PC	495	24,4	**33**	L	ABS	37 x 2 cav.	53
16	G	PMMA (10%-r)	489	29	**34**	L	PA	16,07 x cav.	11,8
17	G	SAN	383	24,5	**35**	L	PP	14,36 x 4 cav.	12,5
18	H	PP	3407	100	**36**	L	HDPE	15 x 4 cav.	15

TABLA 3: DATOS DE LAS PIEZAS INYECTADAS

Se puede consultar más información de cada una de las piezas en la publicación del apartado 9.4, [99].

4.3. Discusión de resultados

A continuación se presentan los consumos reales de las 36 piezas analizadas en la Figura 23, donde cada color corresponde a una máquina de inyección diferente, apareciendo en el orden indicado en la Tabla 3.

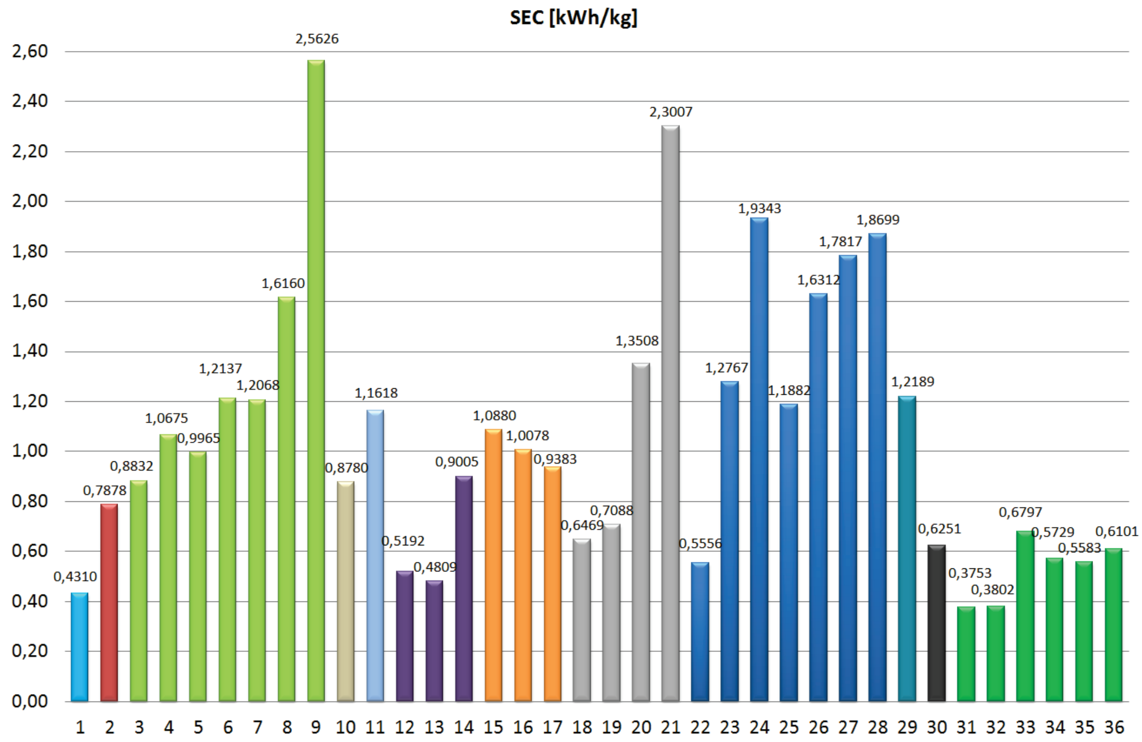

FIGURA 23: CONSUMO ELÉCTRICO EN KWH/KG

Como se indica en el artículo [99], que aparece en el apartado 9, la media de las medidas es de 1,056 kWh/kg, un 28,2% menor que el valor proporcionado por la base de datos EcoInvent. Además, la variabilidad es alta (σ= 0,543kWh/kg). Destacando el ahorro eléctrico que proporciona el uso de la máquina de inyección eléctrica.

El máximo SEC lo registra la pieza número 9 (2,563 kWh/kg) inyectada en la máquina C, de 3000 toneladas de fuerza de cierre. La máquina eléctrica de 85 toneladas requiere el menor consumo eléctrico de todas las medidas, en el procesado de la pieza 31 (0,375 kWh/kg).

De los resultados se aprecia que no existe relación directa entre el SEC obtenido y el tamaño de la máquina. Sin embargo, sí existe una tendencia clara entre el consumo y los kg/h inyectados, siendo éste más bajo con valores altos de productividad, Figura 24.

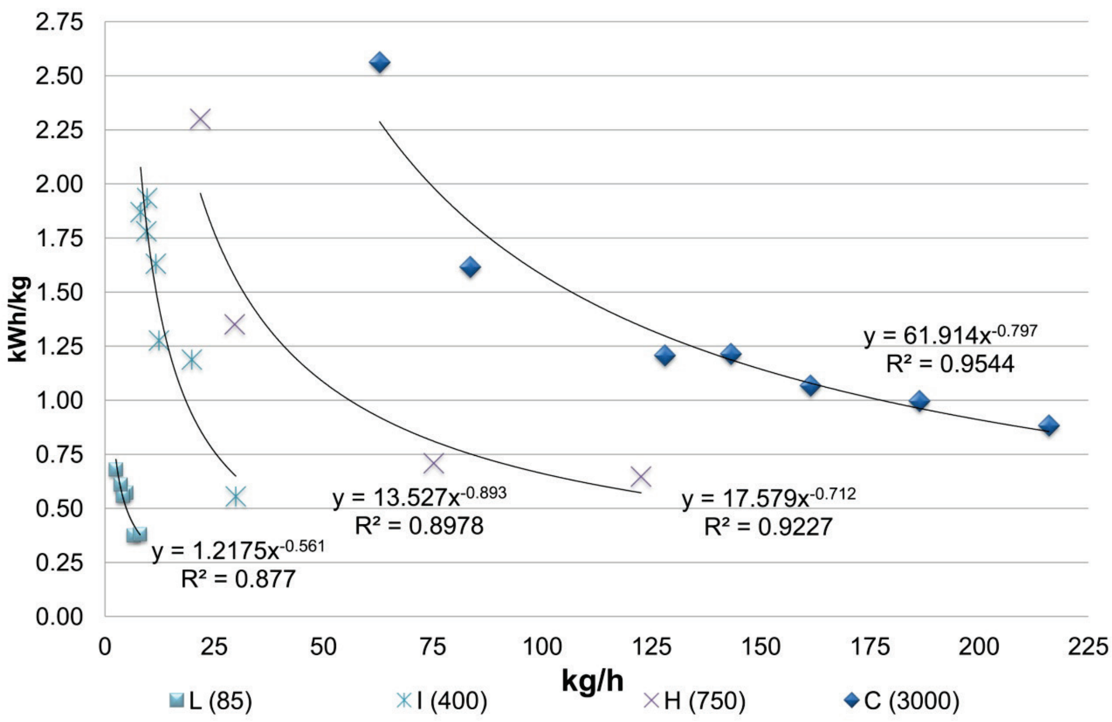

FIGURA 24: SEC VS KG/H, [99]

Esta tendencia se caracteriza con el valor de correlación R^2, y posee sentido físico debido a que el consumo constante que requiere la máquina para funcionar durante los tiempos muertos, es dividido entre un número mayor de kilogramos hora, resultando en consumos menores. Este análisis de regresión lineal (LRA), resulta un método útil para identificar buenas prácticas y establecer líneas de referencia en benchmarking, [100].

Por otro lado, se identifica que cuanto mayor sea el porcentaje de utilización de la máquina de inyección menor consumo eléctrico se obtiene.

Capítulo 5

MODELO EMPÍRICO

5. Modelo empírico

Debido a que no siempre puede ser posible realizar medidas in situ, con los resultados de las medidas experimentales se ha construido un modelo empírico con el objetivo de realizar una estimación del consumo eléctrico del proceso de inyección en función de unos pocos parámetros de fácil obtención. El proceso de obtención de este modelo se ha realizado de forma iterativa, mediante una hoja de cálculo, buscando optimizar a cada paso, los errores de estimación del modelo experimental.

Los parámetros que se han seleccionado para generar el modelo matemático han sido los siguientes:

- Porcentaje de utilización de la máquina (η)
- Eficiencia de la máquina de inyección (E)
- kg/h
- Termoplástico (calor específico (c_e) y diferencia de temperatura de inyección y ambiente (ΔT))

Como se muestra en la última publicación que cierra la unidad temática de esta tesis doctoral, se realizaron dos pasos para ajustar el modelo. En primer lugar, se modeló la relación entre el porcentaje de uso de la máquina y la eficiencia de la misma, de acuerdo a la siguiente ecuación:

$$SEC\ \left(\frac{kWh}{kg}\right) = \left(7.5 - \frac{5\ .E}{100}\right) x\ \sqrt{\eta}$$

siendo

$$\eta = \frac{w}{\rho\ .V_{max}}.100$$

donde w, es el peso bruto inyectado de la pieza, ρ, la densidad del material, y V_{max}, el volumen máximo que la máquina de inyección es capaz de inyectar.

En la Figura 25, se pueden observar como las medidas experimentales quedan englobadas dentro de las tres curvas del modelo correspondientes a eficiencias baja, media y alta, respectivamente.

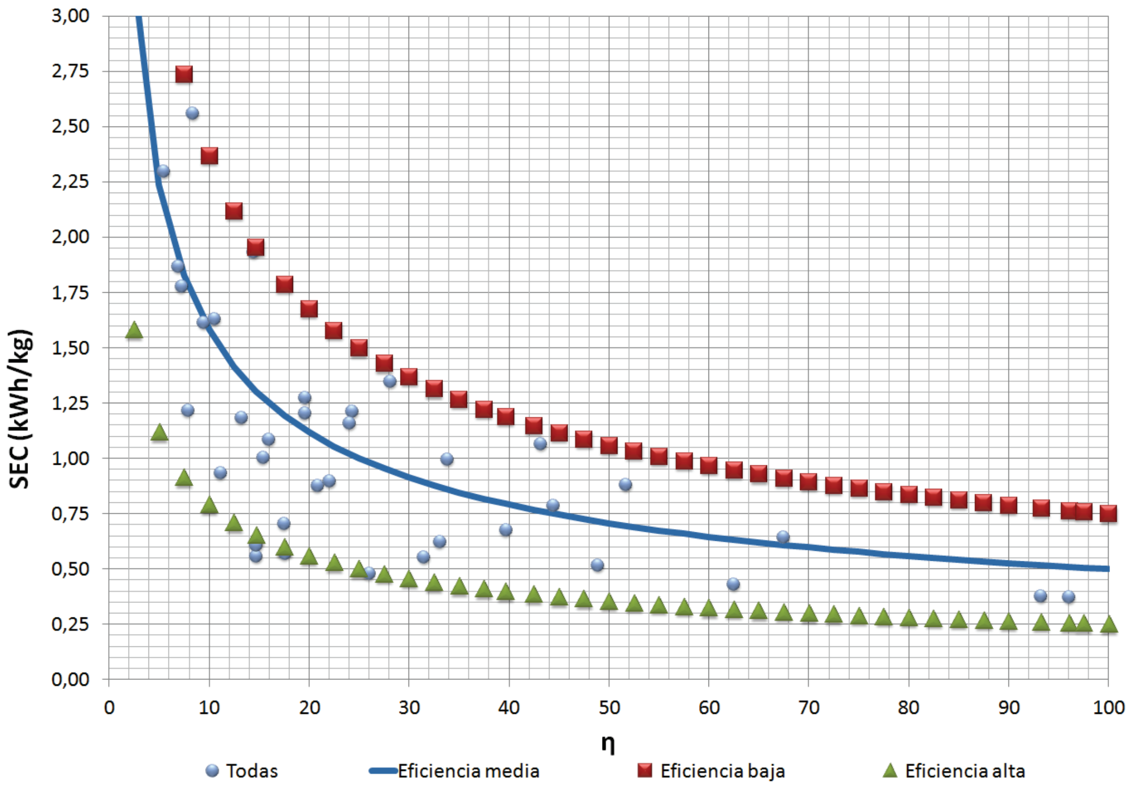

FIGURA 25: MODELO EMPÍRICO

De este modo, se está considerando la influencia de la tecnología de la máquina de inyección y cómo de optimizado se encuentra el proceso de fabricación (mediante la relación entre volumen inyectado de pieza y volumen máximo inyectable por la máquina).

A continuación, se incluyen los otros dos factores que modifican la eficiencia supuesta a la máquina (generando un E'). El primero de ellos (CFT), son los kg/h inyectados. Tanto en la revisión del Estado del Arte, como en el análisis de los resultados experimentales, este valor se ha identificado como uno de los más relevantes en el consumo final del proceso de fabricación. A su vez se incluye el material inyectado como factor influyente en el consumo eléctrico (CFP).

Estos dos factores modificadores de la eficiencia se incluyen en el modelo como muestran las siguientes ecuaciones:

$$CFT = \frac{kg/h}{0.051.F_c}$$

$$CFP = \frac{c_e\left[\frac{KJ}{kg.K}\right].(T_{inj} - T_{amb})}{350{,}255}$$

obteniéndose los kg/h, con el peso bruto inyectado por ciclo y el tiempo de ciclo.

Para ambos se han obtenido relaciones en base a datos experimentales.

$$E' = E \cdot \frac{CFT^{0.15}}{CFP^{0.1}}$$

Cuando la pieza cuente con unos kg/h por encima de la media, el factor aumentará la eficiencia del proceso, obteniendo un menor consumo eléctrico. Por otro lado, si el material requiere mayor energía en la fase de plastificación, la eficiencia disminuirá, aumentando el consumo eléctrico.

El criterio de asignación de la eficiencia de la máquina (E), para las medidas experimentales, se ha realizado de acuerdo a la antigüedad de las máquinas, y a su tecnología (asignando la mayor eficiencia a la máquina eléctrica de 85 toneladas de fuerza de cierre).

En la Figura 26, que se muestra a continuación, se representan los consumos reales de pieza, frente a la estimación del modelo empírico y el valor proporcionado por la base de datos EcoInvent.

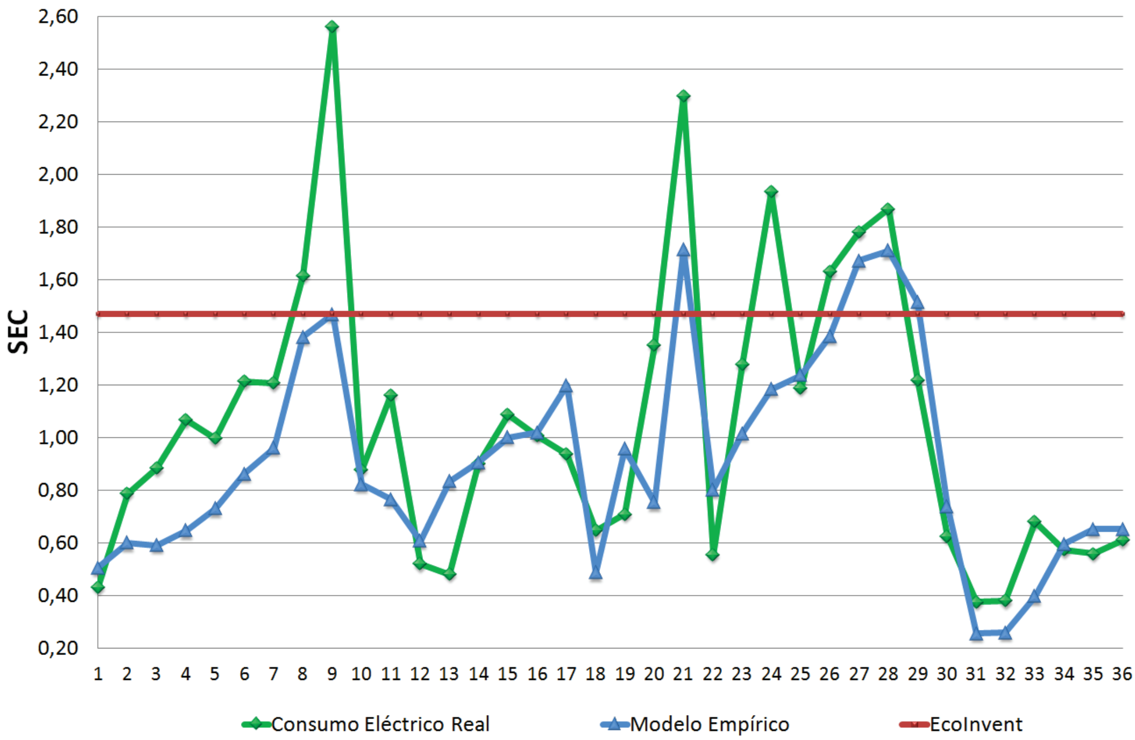

FIGURA 26: COMPARACIÓN DE RESULTADOS: MODELO EMPÍRICO, REAL Y DATO DE ECOINVENT

Finalmente, la ecuación completa del modelo empírico depende de la eficiencia de la máquina (E), la fuerza de cierre de la máquina, Fc (en toneladas), los kg/h inyectados, por lo que el tiempo de ciclo también tiene influencia en el consumo, el calor específico del material, la temperatura de inyección del material y del ambiente y el porcentaje de utilización de la máquina, que depende del peso de la pieza, la densidad del material y el volumen máximo inyectable por la máquina de inyección.

$$SEC\ \left(\frac{kWh}{kg}\right) = \left(7.5 - \left(5.\frac{E}{100}.\frac{\left(\frac{kg/h}{0.051.F_c}\right)^{0.15}}{\left(\frac{c_e.(T_{inj} - T_{amb})}{350,255}\right)^{0.1}}\right)\right) x\ \sqrt{\frac{w}{\rho\ .V_{max}}.100}$$

Mediante el uso de este modelo se obtiene un promedio de error en absoluto para las 36 medidas indicadas en el apartado 4, en porcentaje, de 22,5% frente al 86,85% que se obtendría haciendo uso del valor proporcionado por la base de datos EcoInvent.

La pieza 9, es la que registra una desviación mayor en kWh/kg, entre el consumo real y el estimado. En este caso, esta pieza está inyectada en una de las máquinas de inyección más grandes (3000 toneladas), y resulta más costosa de procesar por su espesor, por lo que el tiempo de ciclo es alto, en comparación con piezas similares inyectadas en la misma máquina. Este hecho provoca que se obtenga un valor bajo de kg/h inyectados, lo que unido a un porcentaje de utilización bajo, genera un alto consumo eléctrico. Como se puede observar en la Figura 25, para porcentajes bajos de η, el modelo tiene una mayor dispersión, resultando más sensible a cambios de E'.

De este modo los parámetros para obtener el valor de SEC, se reducen a nueve:

1. Eficiencia
2. Fuerza de Cierre
3. Peso bruto inyectado
4. Tiempo de ciclo
5. Calor específico del material
6. Temperatura de inyección
7. Temperatura ambiente
8. Densidad del material
9. Volumen máximo inyectable por la máquina

Capítulo 6

CONCLUSIONES

6. Conclusiones

Conforme se han completado las distintas fases de la investigación se han ido extrayendo conclusiones, que han derivado en las diversas publicaciones presentadas.

Los datos utilizados en el inventario del ciclo de vida suponen la clave para la obtención de unos resultados precisos en la evaluación del impacto ambiental o económico de una pieza. Esta conclusión se obtuvo del análisis de sensibilidad realizado sobre el dataset de EcoInvent, donde por ejemplo se identificó que los aditivos considerados, específicos del procesado del PVC; suponían el incremento de 14.2 mPt/kg. Estos resultados indican la necesidad de realizar un estudio en detalle que permita identificar de manera correcta acciones de mejora. El entender en qué se basan los datos utilizados para el cálculo de impacto ambiental, mediante metodologías como ReCiPe, permite a su vez evitar errores en análisis de ciclo de vida completos, donde por ejemplo se podría considerar erróneamente la calefacción de la fábrica de procesado de forma duplicada. A su vez, debido a la gran influencia del consumo eléctrico del proceso en el resultado total, se detectó de forma clara la necesidad de medir consumos reales.

Las medidas experimentales realizadas durante la investigación reflejaron una alta variabilidad (0,3 a 2,6 kWh/kg), en función del tipo de pieza, material y máquina de inyección utilizada, mostrando una clara tendencia descendente a mayor valor de kg/h inyectados. El uso de la metodología 2, mostrada en este documento reflejaba la importancia de conocer con exactitud este consumo eléctrico, suponiendo éste porcentajes superiores al 90% del resultado global de impacto, en la mayoría de las categorías de impacto estudiadas.

Del total de piezas medidas se ha obtenido una media de consumo eléctrico de 1,056 kWh/kg, un 28,2% menor que el valor constante proporcionado por EcoInvent, obteniendo una desviación estándar alta de 0,543 kWh/kg. Los valores mínimos de consumo se registraron en el procesado de piezas con máquina eléctrica (0,375 kWh/kg y una media de 0,529kWh/kg), por lo que invertir en esta tecnología es una gran acción de mejora.

Otra de las tendencias detectadas es la relación entre el consumo y el porcentaje de utilización de la máquina, siendo éste menor cuanto más optimizado esté la relación pieza/máquina. Entre todas las medidas realizadas se pudieron establecer algunas relaciones entre piezas con características similares y una diferente, como, por ejemplo, mismo molde y máquina y distinto material. El calor específico contribuye a la demanda de energía del proceso de plastificación. A su vez, los requerimientos de refrigeración son diferentes en función del material, lo que se refleja en el SEC global.

Gracias a las mediciones realizadas se ha podido construir de forma iterativa, un modelo empírico que permite estimar de forma rápida y con mayor precisión que haciendo uso de los valores de bases de datos, el consumo eléctrico del proceso de inyección y por tanto su impacto, ambiental y económico, si no es posible realizar medidas en fábrica.

Este modelo requiere nueve parámetros de fácil obtención, al estar relacionados directamente con la pieza y la máquina utilizadas.

Mediante el uso de la aplicación informática desarrollada en esta tesis doctoral, se derivan varias conclusiones a raíz de los resultados de los casos de aplicación en piezas completas. Estos resultados se presentan de forma absoluta y porcentual, permitiendo ésta última comparar entre casos (piezas de pequeño y gran tamaño).

- Producción de la materia prima: El impacto ambiental de la producción de la materia prima utilizada en la pieza supone en la mayoría de los casos un porcentaje entre el 75 y el 85% utilizando la metodología ReCiPe y un 85-90% en la categoría de la huella de carbono. En el coste económico se sitúa en el 70-75% del resultado global. Cabe destacar que los termoplásticos más técnicos como son los policarbonatos, las poliamidas con o sin carga, ABS...etc. que suelen tener un coste más elevado por sus mayores prestaciones, también repercuten en un alto impacto ambiental, en comparación con materiales commodities, como los polipropilenos o polietilenos cuyo impacto y coste es menor.

- Distribución de la materia prima a la planta de procesado: En cuanto a la fase de distribución de la materia prima a la planta de procesado, supone un porcentaje poco relevante en el resultado global (0.5-3% en el impacto ambiental). Dentro de la metodología, en esta etapa del ciclo de vida, no se consideraba el coste al suponer que está incluido dentro del precio de la materia prima. Remarcar que el impacto del embalaje dentro de esta fase resulta más significativo si la distancia a recorrer es menor, por lo que la reutilización del mismo es aconsejable.

- Proceso de inyección: tras la fase de producción, es la etapa más relevante. Supone entre un 5-15% en las categorías de impacto ambiental y hasta un 25% del coste de la pieza. Como se ha venido tratando a lo largo de toda la investigación, el consumo eléctrico es el factor dominante suponiendo entre 80-90% del impacto ambiental del proceso. Al contrario que en otras fases el porcentaje del coste económico no va tan alineado, ya que las amortizaciones de máquina y molde y los costes de operario, tienen cierto peso sobre el resultado. En este apartado el mix eléctrico que seleccionemos en la aplicación tiene una gran importancia sobre el resultado. De este modo, una pieza puede tener hasta ocho veces más impacto ambiental si es inyectada en China que si se realiza en Francia, debido a la procedencia de la energía. Respecto a la maquinaria utilizada y el molde de la pieza, mediante la metodología propuesta se observa en los casos estudiados que la importancia del coste (60-75%) es mayor que la del impacto ambiental (15-20%). Esto se debe, como se ha mencionado a que los costes de las amortizaciones y los operarios predominan sobre el gasto del consumo eléctrico. Este hecho se acentúa en máquinas que procesan menos kilogramos de plástico al repartirse los costes entre un número menor de kilogramos. Por tanto, para piezas pequeñas el coste del procesado cobra mayor peso frente al coste de material. El posible reciclaje de los metales permitiría reducir el impacto ambiental de este apartado. Finalmente, el impacto del mantenimiento resulta irrelevante en las dos dimensiones calculadas (0.5-2%).

- <u>Embalaje</u>: La opción de incluir embalaje para la distribución a cliente de la pieza no aumenta demasiado el resultado total, siendo junto con la distribución de la materia prima una de las etapas con menor impacto. Piezas de tamaño pequeño permiten optimizar el transporte, suponiendo un menor impacto. Se ha supuesto una alta reutilización de los materiales por lo que si esta práctica no se realizara los resultados se verían incrementados en un orden de magnitud.

- <u>Distribución a cliente</u>: Si se hace uso del embalaje, esta segunda etapa de distribución resulta algo más perjudicial para el medio ambiente que la de la materia prima, al aumentar el peso a transportar (2-10% en ReCiPe, 4-15% del coste económico). El barco es el medio de transporte con menor impacto ambiental por kilómetro, aunque en general, cuando éste se utiliza, las distancias recorridas son mucho mayores.

- <u>Fin de vida</u>: según el tratamiento que tengan la materia prima de la pieza y su embalaje, el impacto ambiental se verá incrementado o reducido. Las opciones que se consideran son el reciclaje, el envío a vertedero y la valorización.
  Los porcentajes de reciclaje de las piezas de plástico son todavía bajos, siendo el envío a vertedero la opción más utilizada, porque en general, esta etapa siempre va a incrementar el resultado de impacto. Plásticos como los polietilenos de alta o baja densidad, el PET o los polipropilenos, sí son reciclados en algún porcentaje, según se refleja en el informe IEC TR 62635, [95].
  Una medida positiva a realizar en las fábricas de procesado, con la que se obtienen reducciones de impacto ambiental y ahorro en coste, es con el triturado de las coladas o rechazos de las piezas inyectadas.
  Respecto al fin de vida de los materiales de embalaje, el cartón destaca como el material que se recicla en mayor porcentaje, reduciendo el resultado global. Eurostat proporciona valores de porcentaje, distinguiendo entre países, [96]. A

futuro estos valores deberán verse incrementados por el aumento de las exigencias ambientales y también con el avance de las tecnologías de reciclaje.

Como se ha visto, existen multitud de parámetros a la hora de analizar la sostenibilidad de una pieza de plástico. Generalmente se pone especial atención en la selección de material y en el diseño de la pieza, sin embargo éstos vienen en muchas ocasiones delimitados por unos requerimientos de diseño, dejando poco margen de mejora. Otros aspectos donde el ingeniero tiene poder de decisión, como en la elección de máquina en el procesado, cobran también importancia al estar directamente relacionados con el consumo eléctrico del proceso y éste a su vez con el impacto ambiental y económico.

A lo largo de esta tesis, se ha revisado el estado del arte para identificar los potenciales de mejora en este ámbito de investigación. El estudio de la sostenibilidad se ha convertido, debido a la situación de la sociedad actual, en un tema relevante a estudio. Los procesos de fabricación, a gran escala, requieren un análisis en detalle que permita identificar acciones de reducción del impacto. Mediante el uso de sistemas de monitorización de energía o el modelo empírico presentado, se permite calcular de forma más precisa la influencia que puede tener cambios en el proceso, sobre el impacto ambiental y económico de una pieza de plástico inyectada, proporcionando información novedosa tanto a profesionales del ámbito científico y docente, como ingenieros que desempeñen su trabajo en el ámbito fabril.

Capítulo 7

FUTURAS LÍNEAS DE INVESTIGACIÓN

7. Futuras líneas de investigación

A raíz de los resultados obtenidos durante esta investigación, se pueden plantear varias líneas con potencial investigador en futuros estudios.

El procedimiento y metodología mostrados pueden ser usados para analizar otros procesos de fabricación, y más concretamente en el mundo de la inyección de plásticos, profundizar en otras tecnologías como la inyección MuCell o por gas.

Por otro lado, si fuera posible, sería de gran interés el estudiar de forma independiente el consumo eléctrico cada subsistema dentro de la máquina y el proceso de inyección. Así como el realizar medidas experimentales con un mismo molde, inyectando materiales diferentes o en máquinas de inyección distintas, analizando de este modo de forma independiente distintos parámetros.

También aumentar las medidas a otro tipo de materiales, como el PVC, o el PET que son ampliamente utilizados en la industria, aportaría datos de gran valor, o el realizar un análisis de sensibilidad sobre cómo afecta el porcentaje de carga al consumo eléctrico de una pieza de plástico.

A su vez, la realización de más medidas experimentales, permitiría realizar ajustes sobre el modelo empírico construido, en puntos donde la estimación se realiza con mayor error, como por ejemplo con porcentajes bajos de utilización de máquina, donde el modelo presenta mayor incertidumbre en los resultados, para pequeños cambios en la eficiencia del proceso.

Todo ello contribuiría al conocimiento de este campo, permitiendo a futuro el diseñar una pieza o su molde teniendo en cuenta factores como qué tipo de máquina de inyección se encuentra disponible, definir espesores o longitudes de flujo, buscando la combinación más eficiente dentro de las restricciones del proceso.

Capítulo 8

BIBLIOGRAFÍA

8. Bibliografía

[1] I. Boustead, "Eco-Balance Methodology for Commodity Thermoplastics," The European Centre for Plastics in the Environment (PWMI). Later Association of Plastics Manifacturers in Europe (APME), Brussels, 1992.

[2] J. E. Givens and A. K. Jorgenson, "Individual environmental concern in the world polity: A multi level analysis," *Social Science Research,* vol. 42, pp. 418-431, 2013.

[3] N. Czap and H. J. Czap, "An experimental investigation of revealed environmental concern," *Ecological Economics,* vol. 69, pp. 2033-2041, 2010.

[4] J. Guinée, Handbook on Life Cycle Assesment: Operational Guide to the ISO Standards, Leiden, 2002.

[5] ISO, «UNE-EN ISO 14006:2011,» 2011, Sistemas de gestión ambiental. Directrices para la incorporación del ecodiseño.

[6] European Parliament, «Directive 2002/95/EC of the European Parliament and of the Council of 27 January 2003 on the restriction of the use of certain hazardous substances in electrical and electronic equipment,» Official Journal of the European Union, EU Publications Office, Luxembourg, 2003.

[7] European Parliament, «REGULATION (EC) No 1907/2006 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 December 2006 concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH), establishing a European Chemicals Agency,» Official Journal of the European Union, 2006.

[8] European Parliament, «Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on waste electrical and electronic equipment (WEEE),» Official Journal of the European Union, EU Publications Office, Luxembourg, 2012.

[9] European Parliament, «Directive 2005/32/EC of the European Parliament and of the Council of 6 July establishing a framework for the setting of ecodesign requirements for energy-using products,» Official Journal of the European Union, 2005.

[10] European Parliament and the Council, «Directive 2009/125/EC of the European Parliament and the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products (Recast),» Official Journal of the European Union, EU Publications, Brussels, Belgium, 2009.

[11] D. Dornfeld, «Moving towards Green and Sustainable Manufacturing,» *International Journal of Precision Engineering and Manufacturing- Green Technology,* vol. 1, nº 1, pp. 63-66, 2014.

[12] E. Elijido-Ten y P. Clarkson, «Going Beyond Climate Change Risk Management:

Insights from the World's Largest Most Sustainable Corporations,» *Journal of Business Ethics,* pp. 1-23, 2017.

[13] PlasticsEurope, Association of Plastic Manufacturers, «Plastics - the Facts 2017. An analysis of European plastic production, demand and waste data,» Bruselas, 2018.

[14] H. Wang, Y. Wang y Y. Wang, «Cost estimation of plastic injection molding parts through integration of PSO and BP neural network,» *Expert Systems with Applications,* vol. 40, nº 2, pp. 418-428, 2013.

[15] A. Guevara-Morales y U. Figueroa-López, «Residual stresses in injection molded products,» *Journal of Materials Science,* vol. 49, nº 13, pp. 4399-4415, 2014.

[16] M. Crul y J. Diehl, Design for sustainabilty: a Global Guide, United Nations Environment Programme, Delft University of Technology, 2010.

[17] IHOBE, Manual práctico de Ecodiseño, Operativa de implantación en 7 pasos, IHOBE, S.A. Sociedad Pública de Gestión Ambiental. Gobierno Vasco. Departamento de Ordenación del Territorio, Vivienda y Medio Ambiente, 2000.

[18] ISO, UNE-EN ISO 14040: Gestión Ambiental, Análisis del ciclo de vida, Principios y marco de referencia, Madrid: AENOR Asociación Española de Normalización y Certificación, 2006.

[19] ISO, UNE-EN ISO 14044: Gestión ambiental, Análisis del ciclo de vida, Requisitos y directrices., Madrid: AENOR Asociación Española de Normalización y Certificación, 2006.

[20] A. Elduque Viñuales, «Análisis de Ciclo de Vida de una pieza de plástico inyectado para su optimización desde el punto de vista de impacto medioambiental y económico. Aplicación a una herramienta informática,» Universidad de Zaragoza, 2015.

[21] D. Elduque, C. Javierre, C. Pina, E. Martínez y E. Jiménez, «Life cycle assesment of a domestic induction hob: Electronic boards,» *Journal of Cleaner Production,* vol. 76, pp. 74-84, 2014.

[22] C. Pina, D. Elduque, C. Javierre, E. Martínez y E. Jiménez, «Influence of mechanical design on the evolution of the environmental impact of an induction hob,» *International Journal of Life Cycle Assessment,* vol. 20, nº 7, pp. 937-946, 2015.

[23] N. Tangsubkul, P. Beavis, S. Moore, S. Lundie y T. Waite, «Life Cycle Assessment of Water Recycling Technology,» *Water Resource Management,* vol. 19, pp. 521-537, 2005.

[24] E. Martinez, F. Sanz, S. Pellegrini, E. Jiménez y J. Blanco, «Life cycle assessment of a multi-megawatt wind turbine,» *Renewable Energy,* vol. 34, nº 3, pp. 667-673, 2009.

[25] E. Martínez, J. Blanco, E. Jiménez, J. Saenz-Díez y F. Sanz, «Comparative evaluation of life cycle impact assessment software tools through a wind turbine

case study,» *Renewable Energy,* vol. 74, pp. 237-246, 2015.

[26] M. Cellura, S. Longo y M. Mistretta, «Life Cycle Assesment (LCA) of protected crops: an Italian case study,» *Journal of Cleaner Production,* vol. 28, pp. 56-62, 2012.

[27] M. Bortolini, A. Cascini, M. Gamberi, C. Mora y A. Regattieri, «Sustainable design and life cycle assessment of an innovative multi-functional haymaking agricultural machinery,» *Journal of Cleaner Production,* Vols. %1 de %223-36, p. 82, 2014.

[28] J. Rives, J. Rieradevall y X. Gabarrell, «LCA comparison of container systems in municipal solid waste management,» *Waste Management,* vol. 30, pp. 949-957, 2010.

[29] L. Tähkämö y L. Halonen, «Life cycle assessment of road lighting luminaires e Comparison of light-emitting diode and high-pressure sodium technologies,» *Journal of Cleaner Production,* vol. 93, pp. 234-242, 2015.

[30] B. Cox y K. Treye, «Environmental and economic assessment of a cracked ammonia fuelled alkaline fuel cell for off-grid power applications,» *Journal of Power Sources,* Vols. %1 de %2322-335, p. 275, 2015.

[31] E. Jiménez, E. Martinez, J. Blanco, M. Pérez y C. Graciano, «Methodological approach towards sustainability by integration of environmental impact in production system models through life cycle analysis: Application to the Rioja wine sector,» *SIMULATION,* vol. 90, nº 2, pp. 143-161, 2014.

[32] B. Simon, M. Amor y R. Földenyi, «Life cycle impact assessment of beverage packaging systems: focus on the collection of post-consumer bottles,» *Journal of Cleaner Production,* vol. 112, nº 1, pp. 238-248, 2015.

[33] D. Medeiros, A. O. Tavares, Á. L. Rapôso, S. Rapôso y A. Kiperstok, «Life cycle assessment in the furniture industry: the case study of an office cabinet,» *International Journal of Life Cycle Assessment,* vol. 22, pp. 1823-1836, 2017.

[34] W. Finnegan, M. Yan, N. Holden y J. Goggins, «A review of environmental life cycle assessment studies examining cheese production,» *International Journal of Life Cycle Assessment,* pp. 1-15, 2017.

[35] Y. Dong y S. Thomas, «Comparing the midpoint and endpoint approaches based on ReCiPe - a study of commercial buildings in Hong Kong,» *Internation Journal of Life Cycle Assessment,* vol. 19, nº 7, pp. 1409-1423, 2014.

[36] M. Goedkoop, M. Oele, A. de Schryver y M. Vieira, «SimaPro 7 Database Manual. Methods Library,» PRé, Amersfoort, 2010.

[37] M. Goedkoop, R. Heijungs, M. Huijbregts, J. Strujis y R. van Zelm, «ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, Report I: Characterisation,» 2009. [En línea]. Available: http://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf.

[Último acceso: 20 Marzo 2015].

[38] P. Wäger, R. Hischier y M. Eugster, «Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): A follow-up,» *Science of the Total Environment,* vol. 409, pp. 1746-1756, 2011.

[39] H. Monteiro y F. Freire, «Life-cycle assessment of a house with alternative exterior walls: Comparison of three impact assessment methods,» *Energy and Buildings,* vol. 47, pp. 572-583, 2012.

[40] M. Goedkoop, M. Oele, J. Leijting, T. Ponsioen y E. Meijer, «SimaPro 8. Introduction to LCA with SimaPro,» PRé, Amersfoort, The Netherlands, 2013.

[41] B. Weidema, C. Bauer, R. Hischier, C. Mutel, T. Nemecek, J. Reinhard y G. Wernet, «Overview and Methodology. Data Quality Guideline for the Ecoinvent Database Version 3. Ecoinvent Report 1 (v3),» Swiss Centre for Life Cycle Inventories, The Ecoinvent Centre, St. Gallen, Suiza, 2013.

[42] EcoInvent, «Making a difference, EcoInvent's global influence,» [En línea]. Available: http://www.ecoinvent.ch. [Último acceso: 23 Septiembre 2014].

[43] R. Hischier, «"Part II Plastics. Life Cycle Inventories of packaging and Graphical Papers. Ecoinvent- Report Nº.11",» Swiss Centre for Life Cycle Inventories, Dübendorf, 2007.

[44] I. Boustead, «Eco-Profiles of the European Plastics Industry. Polymer Conversion. Report 10,» Association of Plastics Manufacturers in Europe (APME) in collaboration with EuPC and supported by EUROMAP, Brussels, 1997.

[45] K. Habersatter, I. Fecker, S. Dall'Acqua, M. Fawer, F. Fallscheer, R. Förster, C. Maillefer, M. Ménard, L. Reusser y C. e. a. Som, «Ökoinventare für Verpackungen,» BUWAL, Bern, Suiza, 1998.

[46] V. Pita, E. Sampaio y E. Monteiro, «Mechanical properties evaluation of PVC/plasticizers and PVC/thermoplastic polyurethane blends from extrusion processing,» *Polymer Testing,* vol. 21, pp. 545-550, 2001.

[47] K. Kellens, W. Dewulf, M. Overcash, M. Hauschild y J. Duflou, «Methodology for systematic analysis and improvement of manufacturing unit process life- cycle inventory (UPLCI)--- CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description,» *Internation Journal of Life Cycle Assessment,* vol. 17, pp. 69-78, 2012.

[48] K. Kellens, W. Dewulf, M. Overcash, M. Hauschild y J. Duflou, «Methodology for systematic analysis and improvement of manufacturing unit process life- cycle inventory (UPLCI)--- CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: case studies,» *Internation Journal of Life Cycle Assessment,* vol. 17, pp. 242-251, 2012.

[49] K. Kellens, W. Dewulf, B. Lauwers, J.-P. Kruth y J. Duflou, «Environmental Impact Reduction in Discrete Manufacturing: Examples for Non-Conventional Processes,»

Procedia CIRP, vol. 6, pp. 27-34, 2013.

[50] J. R. Duflou, K. Kellens, R. Renaldi, Y. Guo y W. Dewulf, «Critical comparison of methods to determine the energy input for discrete manufacturing processes,» *CIRP Annals - Manufacturing Technology,* vol. 61, pp. 63-66, 2012.

[51] J. Duflou, J. Sutherland, D. Dornfeld, C. Herrmann, J. Jeswiet, S. Kara, M. Hauschild y K. Kellens, «Towards energy and resource efficient manufacturing: A processes and systems approach,» *CIRP Ann.- Manufacturing Technology,* vol. 61, pp. 587-609, 2012.

[52] A. Elduque Viñuales, «Análisis del impacto ambiental del proceso de inyección para ser considerado como criterio de diseño y de selección de máquina. Aplicación a una herramienta informática.,» Universidad de Zaragoza, 2014.

[53] J. Aisa, C. Javierre y J. De la Serna, «An example of simulation tools use for large injection moulds design: The CONTENUR 2400 l solid waste container,» *Journal of Materials Processing Technology,* vol. 175, nº 1-3, pp. 15-19, 2006.

[54] A. Gerber, R. Dubay y A. Healy, «CFD- based predictive control of melt temperature in plastic injection molding,» *Applied Mathematical Modelling,* vol. 30, pp. 884-903, 2006.

[55] S. Kitayama y S. Natsume, «Multi-objective optimization of volume shrinkage and clamping force for plastic injection molding via sequential approximate optimization,» *Simulation Modelling Practice and Theory,* vol. 48, pp. 35-44, 2014.

[56] Y. Wang, K.-M. Yu y C. C. Wang, «Spiral and conformal cooling in plastic injection molding,» *Comput. Aided Des,* vol. 63, pp. 1-11, 2015.

[57] S.-C. Nian, S.-W. Tsai, M.-S. Huang, R.-C. Huang y C.-H. Chen, «Key parameters and optimal design of a single-layered induction coil for external rapid mold surface heating,» *Int Commun Heat Mass Transf,* vol. 57, pp. 109-117, 2014.

[58] G. Wang, G. Zhao y X. Wang, «Development and evaluation of a new rapid mold heating and cooling method for rapid heat cycle molding,» *Int J Heat Mass Transf,* vol. 78, pp. 99-111, 2014.

[59] N. Lu, G. Gong y X. Wang, «Multi-objective process parameter optimization for energy saving in injection molding process,» *Journal of Zhejiang University SCIENCE A,* vol. 13, nº 5, pp. 382-394, 2012.

[60] H. S. Park y T. T. Nguyen, «Optimization of injection molding process for car fender in consideration of energy efficiency and product quality,» *J Comput Des Eng,* vol. 1, nº 4, pp. 256-265, 2014.

[61] H. Park, X. Dang, A. Roderburg y B. Nau, «Development of plastic front side panels for green cars,» *CIRP Journal of Manufacturing Science and Technology,* vol. 6, pp. 44-52, 2013.

[62] M. Packianather, F. Chan, S. Griffiths, S. Dimov y D. Pham, «Optimisation of micro injection moulding process through design of experiments,» *CIRP 12,* pp. 300-305,

2013.

[63] A. Thiriez and T. Gutowski, "An environmental analysis of injection molding," Massachusetts Institute of Technology, Cambridge, 2006.

[64] T. D. J. Gutowski y A. Thiriez, «Electrical Energy Requirements for Manufacturing Processes,» de *13th CIRP International Conference of Life Cycle Engineering*, Lueven, 2006.

[65] A. Lechner, «Advantages of Servo-Driven Hydraulics For Large Injection Machines,» Plastics Technology, May 2013. [En línea]. Available: http://www.ptonline.com/articles/advantages-of-servo-driven-hydraulics-for-large-injection-machines. [Último acceso: March 2016].

[66] M.-S. Huang, T.-Y. Lin y R.-F. Fung, «Key design parameters and optimal design of a five-point double-toggle clamping mechanism,» *Applied Mathematica lModelling,* vol. 35, pp. 4304-4320, 2011.

[67] Y. Hsu, M. Huang y R. Fung, «Energy-saving trajectory planning for a toogle mechanism driven by a PMSM,» *Mechatronics,* vol. 24, pp. 23-31, 2013.

[68] M. Knights, «Electric, Hydraulic or Hybrid? What's the Right Injection Press for You?,» Plastics Technology, 2007. [En línea]. Available: http://www.ptonline.com/articles/electric-hydraulic-or-hybrid-what's-the-rightinjection-press-for-you. [Último acceso: 22 Diciembre 2017].

[69] E. A. Muccio, Plastics Proccesing Technology, Materials Park, Ohio: ASM International, 1994.

[70] D. N. F. d. Almeida, "Life Cycle Engineering aproach to analyse the performance of biogradable injection moulding plastics," 2011.

[71] I. Ribeiro, P. Peças y E. Henriques, «Incorporating tool design into a comprehensive life cycle cost framework using the case of injection molding,» *Journal of Cleaner Production,* vol. 53, pp. 297-309, 2013.

[72] G. Lucchetta y P. Bariani, «Sustainable design of injection moulded parts by material intensity reduction,» *CIRP Annals - Manufacturing Technology,* vol. 59, pp. 33-36, 2010.

[73] E. Müller, R. Schillig, T. Stock y M. Schmeiler, «Improvement of injection moulding processes by using dual energy signatures,» *Procedia CIRP,* vol. 14, pp. 704-709, 2014.

[74] J. Madan, M. Mani, J. H. Lee y K. W. Lyons, «Energy performance evaluation and improvement of unit-manufacturing processes: injection molding case study,» *Journal of Cleaner Production,* vol. 105, pp. 157-170, 2015.

[75] R. Yam y D. Tak, «A cleaner production of rice husk-blended polypropylene eco-composite by gas-assisted injection moulding,» *Journal of Cleaner Production,* vol. 67, pp. 277-284, 2014.

[76] T. Spiering, S. Kohlitz, H. Sundmaeker y C. Herrmann, «Energy efficiency

benchmarking for injection moulding processes,» *Robot Cim- Int Manuf,* vol. 36, pp. 45-59, 2015.

[77] M. U. Uluer, H. O. Unver, G. Gok, N. Fescioglu-Unver y S. E. Kilic, «A framework for energy reduction in manufacturing process chains (E-MPC) and a case study from the Turkish household appliance industry,» *J Clean Prod,* vol. 112, pp. 3342-3360, 2016.

[78] J. Aurich, B. Linke, M. Hauschild, M. Carrella y B. Kirsch, «Sustainability of abrasive processes,» *CIRP Annals- Manufacturing Technology ,* vol. 62, pp. 653-672, 2013.

[79] W. Li, M. Winter, S. Kara y C. Herrmann, «Eco-efficiency of manufacturing processes: A grinding case,» *CIRP Annals - Manufacturing Technology,* vol. 61, pp. 59-62, 2012.

[80] Y. He, Y. Li, T. Wu y J. W. Sutherland, «An energy-responsive optimization method for machine tool selection and operation sequence in flexible machining job shops,» *J Clean Prod,* vol. 87, pp. 245-254, 2015.

[81] P. Mativenga y M. Rajemi, «Calculation of optimum cutting parameters based on minimum energy footprint,» *CIRP Ann - Manuf Techn,* vol. 60, pp. 149-152, 2011.

[82] W. Lee, C. Lee y B. Min, «Simulation-Based Energy Usage Profiling of Machine Tool at the Component Level,» *Internacional Journal of Precision Engineering and Manufacturing-Green Technology,* vol. 1, nº 3, pp. 183-189, 2014.

[83] T. Behrendt, A. Zein y S. Min, «Development of an energy consumption monitoring procedure for machine tools,» *CIRP Ann - Manuf Techn,* vol. 61, pp. 43-46, 2012.

[84] O. I. Avram y P. Xirouchakis, «Evaluating the use phase energy requirements of a machine tool system,» *J Clean Prod,* vol. 19, pp. 699-711, 2011.

[85] S. Kara y W. Li, «Unit process energy consumption models for material removal processes,» *CIRP Ann - Manuf Techn,* vol. 60, pp. 37-40, 2011.

[86] C. Abeykoon, A. L. Kelly, E. C. Brown, J. Vera-Sorroche, P. D. Coates, E. Harkin-Jones, K. B. Howell, J. Deng, K. Li y M. Price, «Investigation of the process energy demand in polymer extrusion:A brief review and an experimental study,» *Appl. Energy,* vol. 136, pp. 726-737, 2014.

[87] C. Abeykoon, A. L. Kelly, J. Vera-Sorroche, E. C. Brown, P. D. Coates, J. Deng, K. Li, E. Harkin-Jones y M. Price, «Process efficiency in polymer extrusion: Correlation between the energy demand and melt thermal stability,» *Applied Energy,* vol. 135, pp. 560-571, 2014.

[88] J. Deng, K. Li, E. Harkin-Jones, M. Price, N. Karnachi, A. Kelly, J. Vera-Sorroche, P. Coates, E. Brown y M. Fei, «Energy monitoring and quality control of a single screw extruder,» *Appl. Energy,* vol. 113, pp. 1775-1785, 2014.

[89] A. Chiarini, «Sustainable manufacturing-greening processes using specific Lean Production tools: an empirical observation from European motorcycle component

manufacturers,» *J Clean Prod,* vol. 85, pp. 226-233, 2014.

[90] W. M. Cheung, J. T. Leong y P. Vichare, «Incorporating lean thinking and life cycle assessment to reduce environmental impacts of plastic injection moulded products,» *Journal of Cleaner Production,* vol. 167, pp. 759-775, 2017.

[91] N. Weinert, S. Chiotellis y G. Seliger, «Methodology for planning and operating energy-efficient production systems,» *CIRP Ann - Manuf Techn,* vol. 60, pp. 41-44, 2011.

[92] H. Luo, B. Du, G. Q. Huang, H. Chen y X. Li, «Hybrid flow shop scheduling considering machine electricity consumption cost,» *Int J Prod Econ,* vol. 146, pp. 423-439, 2013.

[93] European Commission DG Environment, «The COMPetitiveness of EuropeAn Short-sea freight Shipping compared with road and rail transport,» Transport & Mobility Leuven, 2010.

[94] P. A. Wäger y R. Hischier, «Life cycle assessment of post-consumer plastics production from waste electrical and electronic equipment (WEEE) treatment residues in a Central European plastics recycling plant,» *Science of the Total Environment,* vol. 529, pp. 158-167, 2015.

[95] International Electrotechnical Commission, «Guidelines for end-of-life information provided by manufacturers and recyclers and recyclability rate calculation of electrical and electronic equipment,» IEC, Geneva.

[96] EuroStat, «Recycling rates for packaging waste,» Julio 2015. [En línea].

[97] Circutor S.A., «Analizador de reded C-80, Manual de Instrucciones, M98117501-20-10B».

[98] Circutor, «Measurement and electric control, Portable power analyzer».

[99] A. Elduque, D. Elduque, I. Clavería y C. Javierre, « Influence of Material and Injection Molding Machine's selection on the electricity consumption and environmental impact of the injection molding process: an experimental approach,» *International Journal of Precision Engineering and Manufacturing Green Technology,* vol. 5, pp. 13-28, 2018.

[100] Y. S. Tan, T. Bestari Tjandra y B. Song, «Energy Efficiency Benchmarking Methodology for Mass and High-Mix Low-Volume Productions,» *Procedia CIRP 29,* pp. 120-125, 2015.

[101] A. Elduque, C. Javierre, D. Elduque y Á. Fernández, «LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process,» *Sustainability,* vol. 7, pp. 3792-3800, 2015.

[102] A. Elduque, D. Elduque, C. Javierre, Á. Fernández y J. Santolaria, «Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts,» *J Clean Prod,* vol. 108, pp. 80-89, 2015.

[103] A. Elduque, D. Elduque, C. Pina, C. Javierre y Á. Fernández, «LCA Software for

Environmental Impact Assessment of Injected Mould Plastic Parts,» de *27th European Modelling & Simulation Symposium*, Bergeggi, Italia, 2015.

[104] A. Elduque, D. Elduque, I. Clavería y C. Javierre, «Empirical Model to estimate the Electricity Consumption of the Polymer Material Injection Molding Manufacturing Process,» de *The 3rd International Electronic Conference on Materials Sciences*, MDPI, 2018.

Capítulo 9

PUBLICACIONES

9. PUBLICACIONES

9.1 SUSTAINABILITY: LCI DATABASES SENSITIVITY ANALYSIS OF THE ENVIRONMENTAL IMPACT OF THE INJECTION MOLDING PROCESS

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Article

LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process

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Abstract: During the last decades, society's concern for the environment has increased. Specific tools like the Life Cycle Assessment (LCA), and software and databases to apply this method have been developed to calculate the environmental burden of products or processes. Calculating the environmental impact of plastic products is relevant as the global plastics production rose to 288 million tons in 2012. Among the different ways of processing plastics, the injection molding process is one of the most used in the industry worldwide. In this paper, a sensitivity analysis of the environmental impact of the injection molding process has been carried out. In order to perform this study, the EcoInvent database inventory for injection molding, and the data from which this database is created, have been studied. Generally, when an LCA of a product is carried out, databases such as EcoInvent, where materials, processes and transports are characterized providing average values, are used to quantify the environmental impact. This approach can be good enough in some cases but in order to assess a specific production process, like injection molding, a further level of detail is needed. This study shows how the final results of environmental impact differ for injection molding when using the PVC's, PP's or PET's data. This aspect suggests the necessity of studying, in a more precise way, this process, to correctly evaluate its environmental burden. This also allows us to identify priority areas and thereby actions to develop a more sustainable way of manufacturing plastics.

Keywords: environmental impact; injection molding process; LCA

1. Introduction

Over the last decades, society's concern for the environment has increased and changes in legislation of this matter have occurred. Examples of these changes are the European Directive 2012/19/EU, which deals with the waste of electrical and electronic equipment [1], the Ecodesign Directive [2] that establishes design requirements for energy-related and energy-using products, or the REACH regulation, the aim of which is to ensure human health and environmental protection by controlling the use of chemicals [3]. Also specific environmental tools and methodologies have been developed in the last two decades, like the Life Cycle Assessment (LCA), that allows researchers to determine the environmental impact of different products [4,5] or processes [6,7]. In order to apply this tool, a Life Cycle Inventory (LCI) has to be carried out. In this inventory, all the aspects that must be considered in a LCA calculation will be collected [8,9]. To make this task easier, Life Cycle Inventory and environmental impact databases have been created. These databases characterize datasets and their environmental burden. Among the different existent databases, EcoInvent is the most recognized worldwide, with more than 4000 users and including more than 10,000 materials and processes [10]. Also it is integrated in the software SimaPro, which is the world's leading LCA software [11].

The main goal of applying the LCA to a product or a process is to identify the elements that create the most relevant environmental impacts in order to know which elements could be optimized to reduce these impacts [12].

A profound and detailed analysis is needed to calculate the environmental impact of a product or a process. Raw materials consumption, manufacturing processes, distribution, use phase and end-of-life have to be taken into account. LCI databases are used by researchers to perform this task. The collection of real material or energy consumption at machine or process level can be difficult in many cases. Sometimes only data at factory level are available. Research studies like the one developed in the CO2PE!-Initiative [13–17] try to analyze and solve these problems.

Injection molding is one of the plastic manufacturing processes characterized by EcoInvent. This manufacturing process is one of the most commonly used for thermoplastic polymers; therefore, it has economic relevance as global plastics production was 288 million tons in 2012 [18].

Injection molding cycle starts with melting a polymer resin in the injection unit of the injection machine. This is achieved thanks to the heaters and also by means of a rotating screw. The volume of polymer that is going to be injected is called the shot, and when it is ready, it is injected into a cavity which has the negative form of the part that is going to be produced. An injection machine has to provide enough clamping force in order to avoid the plastic from flowing out of the mold, which would cause imperfections in the injected component. The part is ejected once it has solidified and has reached an appropriate temperature thanks to the cooling equipment.

In this paper the injection molding process is studied, analyzing how it is characterized by the most relevant commercial LCI database, EcoInvent. An environmental impact sensitivity analysis has been performed, modifying EcoInvent dataset's values, that use measurements from PVC, PP and PET injection processes. Environmental impact results are calculated with the ReCiPe Endpoint (H/A) methodology [19,20], an endpoint approach that assigns a single value to the harm caused to the environment. This endpoint approach is especially useful to allow engineers and designers to compare different alternatives. This indicator has been the one selected for this study because, although there has been no consensus in the literature about the convenience to use an endpoint approach, as pointed out by Hong Dong and Thomas, when a final result is needed, a methodology like ReCiPe is strongly recommended [21]. SimaPro 8.0.2 [11] and EcoInvent v3 database have been used to perform the calculations shown in this paper.

2. Methods

In order to analyze the injection molding process, first of all, Ecoinvent's characterization has been studied, analyzing its documentation and comparing it with the final dataset in order to establish a connection between it and the original report that was used by EcoInvent [22] to create the dataset (Injection molding {RER}| processing|Alloc Def, U). This analysis is critical to further performing a sensitivity analysis, as it allow us to know how the original data has been adapted by Ecoinvent.

The following summarized table (Table 1), shows the main inventory elements used by Ecoinvent to analyze the environmental impact of the processing of 1 kg of injected plastic. These are based on two original reports of the processing of three different types of plastic: PVC, PP and PET [23,24] and how EcoInvent has adapted these values to create its own average dataset. The final values used in Ecoinvent's dataset are the arithmetic mean of those three different measurements.

Table 1. One-kilogram injection molding process's inventory (Summarized, [22]).

Per kg Output		APME Report		BUWAL Report	EcoInvent Dataset	
	Unit	PVC	PP	PET	Arithmetic mean	EcoInvent v3.0.1. dataset selection
				INPUT		
				Materials		
Lubricants	kg	0.0068			0.0023	Lubricating oil {GLO}| market for|Alloc Def, U
Lubricating oil	MJ	0.0948			0.0316	
Grease	MJ		0.0007		0.0002	
Solvents	kg	0.1349			0.0450	Solvent, organic {GLO}| market for|Alloc Def, U
Filler	kg	0.0227			0.0076	Kaolin {GLO}| market for|Alloc Def, U Malusil {GLO}| market for|Alloc Def, U Lime {GLO}| market for|Alloc Def, U
				Packaging materials		
Wooden Pallets	kg	0.0461	0.05		0.0320	EUR-flat pallet {GLO}| market for|Alloc Def, U
Pallets	kg	0.0005			0.0002	
				Energy		
Electricity	kWh	1.3746	2.096	1	1.4902	Electricity, medium voltage market for|Alloc Def, U
Natural gas	MJ		12.6982		4.2327	Heat, district or industrial, natural gas|market for heat, district or industrial, natural gas|Alloc Def,
				OUTPUT		
				Waste		
Regulated Waste	kg	1.00×10^{-4}			3.3333×10^{-5}	Hazardous waste, for underground deposit {GLO}| market for|Alloc Def, U

Some of the key inventory assumptions made by Ecoinvent are explained in the following paragraphs.

Energy inputs such as natural gas for the plant heating or the consumption of electricity for the machine, are considered in the inventory. Fuels like butane, propane and gasoline, related to internal transports in the plant, are omitted. Elements such solvents, stabilizers, pigments (44% Kaolin, 6% of Malusil (talc) and 50% Lime [25]), fillers or hazardous waste, that are only related to PVC processing are included in the final (average) Ecoinvent dataset, thus influencing all the environmental impact calculations of polymers that do not need these inventory elements for their processing.

The LCI also includes the cooling water used during the process and the wooden pallets used to transport the injected product. Ecoinvent also adds to the dataset an estimation of the infrastructure of the factory.

Considering all the explanations above, several LCIs will be developed, modifying the dataset values, in order to create new scenarios that allow us to perform a sensitivity analysis, and compare them with the generic EcoInvent dataset. These scenarios are based on APME and BUWAL reports for PVC, PP and PET processing [23,24], an updated APME report [26], which analyses PP injection and provides new electricity consumption data for this polymer, and finally a scenario named EcoI3M, which is based on Ecoinvent's dataset, but does not consider in the inventory all the specific aspects of PVC processing. These cases will be addressed in this paper as:

- PVC
- PP
- PET
- PP (2010 Electricity): PP '10
- Generic EcoInvent, omitting specific aspects of PVC processing: EcoI3M

Next table (Table 2) shows the main inventory values considered for each scenario.

Table 2. Inventory values used for calculation.

	Units	EcoInvent v3	PVC	PP	PET	PP '10	EcoI3M
Electricity	kWh	1.480	1.375	2.096	1	0.799	1.480
Heating	MJ	4.439	0.347	13.043	-	13.043	4.439
Lubricant oil	kg	3.03×10^{-3}	9.06×10^{-3}	1.67×10^{-5}	-	1.67×10^{-5}	5.56×10^{-6}
PVC's Additives	kg	0.059	0.174	-	-	-	-
Packaging materials	kg	0.037	0.056	0.056	-	0.056	0.037
Waste	kg	−0.007	−0.010	−0.005	−0.005	−0.005	−0.006

3. Results and Discussion

In this section, after defining the LCI of EcoIvent's dataset, and our new scenarios, some results will be shown in order to understand how these inventory differences modify the environmental impact of the process. Figure 1 shows how the environmental impact under ReCiPe methodology is created for Ecoinvent's "Injection moulding {RER}| processing|Alloc Def, U" dataset. Electricity consumption creates most of the environmental impact (62.6%). Natural gas and other fuels used for heating of the plant create around 16% of the overall impact, whilst all the used packaging materials generate 7% of the impact. The consumption of different types of additives (lubricants, solvents, stabilizers, pigments and fillers such as kaolin, lime and malusil) represents almost 13% of the result.

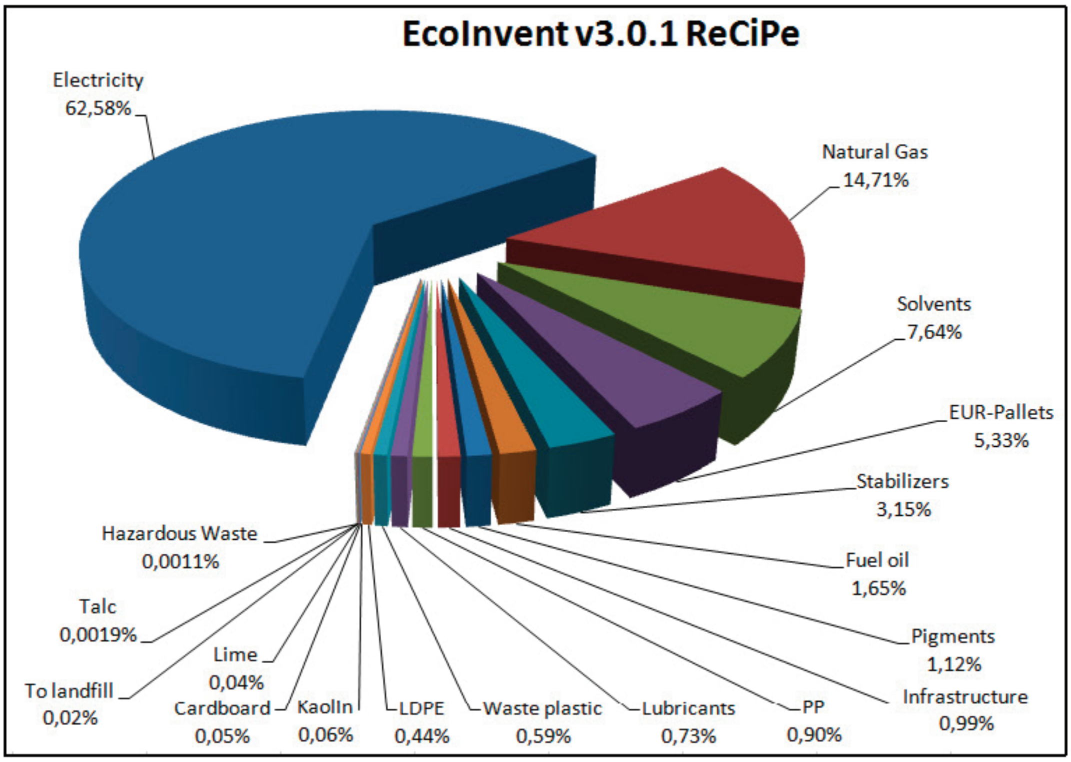

Figure 1. EcoInvent v3 results, ReCiPe methodology.

Figure 2 shows a comparison of the environmental impact for Ecoinvent's dataset and all the previously proposed scenarios. The environmental impact of the PVC processing scenario is about 8% higher than the results of the EcoInvent average dataset. The PP case is the one that has the greater environmental impact (162.99 mPt/kg) due to a higher value of energy consumption, with an impact 46.83% bigger than EcoInvent. When modifying the value of the electricity consumption for a more recent measurement (PP '10 scenario), such as the one registered in [26], 0.7922 kWh/kg, the environmental impact of the process is reduced to 102 mPt/kg, 8% lower than the EcoInvent v3 case. The most relevant variation when comparing with Ecoinvent (−56.2%), is the one achieved by the PET processing, whose LCI inventory is not as complete as the one considered in other polymers. Finally, the scenario EcoI3M shows an impact 14.24 mPt/kg lower than Ecoinvent's due to the removal from the inventory of the specific additives of the PVC processing.

Table 3 shows how the environmental impact of each scenario is created, dividing it in the main groups of the LCI. Electricity consumption is the main factor, creating between 36.7% and 96.6% of the environmental impact. In PET processing it achieves a 96.55% due to a simplified LCI data.

The heating contribution represents a relevant percentage in the generic case of EcoInvent v3 (16.36%). However, this is caused by PP's data, as neither the PVC nor the PET have natural gas heating in their LCI data.

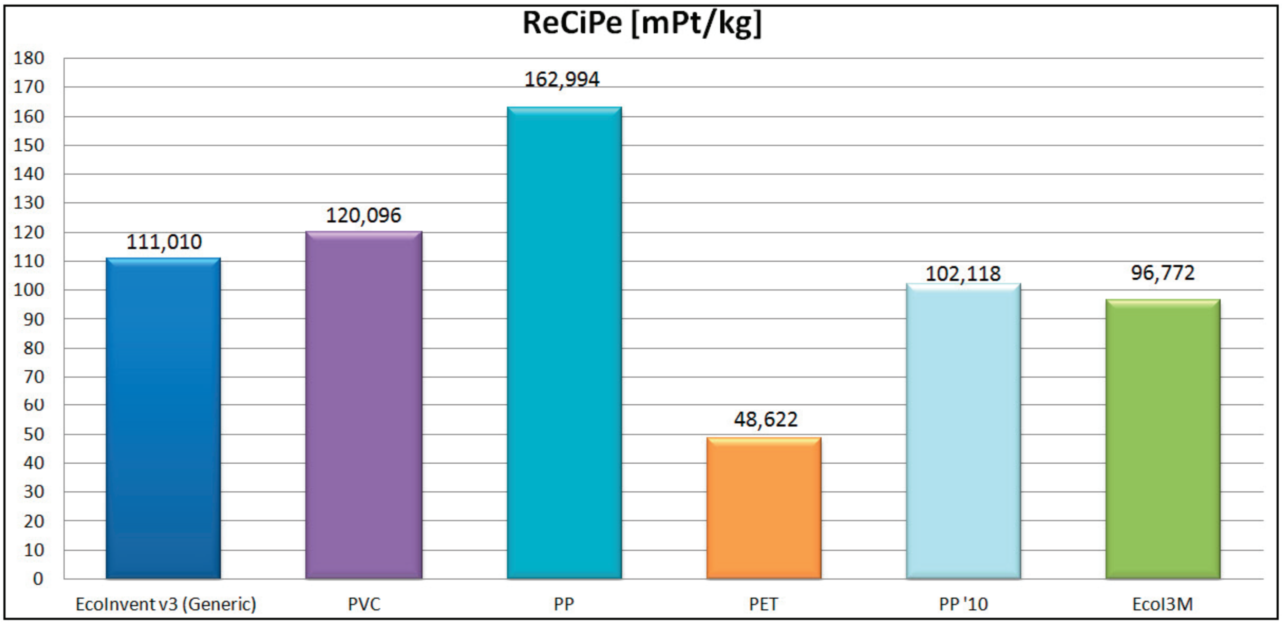

Figure 2. Environmental impact results for the injection molding process, ReCiPe EndPoint (H/A).

Table 3. Percentage distribution of environmental impact in the injection process.

	EcoInvent v3	**PVC**	**PP**	**PET**	**PP '10**	**EcoI3M**
Electricity	62.58%	53.73%	60.37%	96.55%	36.74%	71.79%
Heating	16.36%	2.31%	31.90%	-	50.92%	18.76%
Lubricant oil	0.73%	2.02%	0.003%	-	0.004%	0.002%
PVC's additives	12.01%	30.79%	-	-	-	-
Packaging materials	6.71%	9.48%	6.70%	-	10.69%	7.63%
Waste	0.62%	0.75%	0.36%	1.20%	0.57%	0.68%
Infrastructure	0.99%	0.91%	0.67%	2.26%	1.07%	1.13%

PVC's additives create around 12% of the environmental impact in Ecoinvent's dataset (31% in PVC scenario), but are not present in the other scenarios. Packaging materials create between 6.7% and 10.7% of the environmental impact.

Finally, the contributions of waste and infrastructure are low (<2.5%) for every studied scenario.

4. Conclusions

This study has shown how the environmental impact results for the injection molding process vary when modifying some of the main Life Cycle Inventory values, obtaining a great difference between different reports. Electricity's contribution to the environmental impact of the process varies between 37.5–87.6 mPt/kg in all the studied scenarios.

These results have revealed how the specific PVC's additives contribute to increase the final results of EcoInvent's dataset in +14.24 mPt/kg. Analyzing the three plastics studied in the report, the PP scenario has the higher impact due to its higher energy consumption (2.096 kWh/kg), as electricity consumption is the most relevant factor in the final results.

All these considerations imply that a deeper study is needed to assess correctly the environmental performance of a specific injection process in order to propose actions that will achieve a more sustainable development in the industry. The study of how the LCI databases characterizes this type of manufacturing processes can prevent double counting in LCA analysis, since, for example, the facility heating could be considered twice without noticing it.

In summary, the results presented in this paper indicate the necessity of measuring real processes because of the high variability in the LCI data, as its influence has been demonstrated in the results of environmental impact of a widely used manufacturing process.

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Author Contributions

Ana Elduque is a Ph.D. student who reviewed the state of the art, processed the data and made the calculations with the environmental impact assessment software SimaPro also in collaboration with Daniel Elduque, a researcher in the field of environmental impact. Carlos Javierre which is the director of the doctoral thesis, carried out the first draft version of the manuscript. Ángel Fernández helped with the analysis of the results and its conclusions. All of the authors have contributed to the writing and correction of this article and they all agree to its final version.

Conflicts of Interest

The authors declare no conflict of interest.

References

1. European Parliament. *Directive 2012/19/EU of the European Parliament and of the Council of 4 July 2012 on Waste Electrical and Electronic Equipment (WEEE)*; Official Journal of the European Union, EU Publications Office: Luxembourg, 2012.
2. European Parliament and the Council. *Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products (Recast)*; Official Journal of the European Union, EU Publications Office: Brussels, Belgium, 2009.
3. European Parliament and the Council. *Regulation (EC) N° 1907/2006 of the European Parliament and of the Council of 18 December 2006 Concerning the Registration, Evaluation, Authorisation and Restriction of Chemicals (REACH)*; Official Journal of the European Union: Brussels, Belgium, 2006.
4. Elduque, D.; Javierre, C.; Pina, C.; Martínez, E.; Jiménez, E. Life cycle assesment of a domestic induction hob: Electronic boards. *J. Clean. Prod.* **2014**, *76*, 74–84.
5. Martínez, E.; Blanco, J.; Jiménez, E.; Saenz-Díez, J.; Sanz, F. Comparative evaluation of life cycle impact assessment software tools through a wind turbine case study. *Renew. Energy* **2015**, *74*, 237–246.

6. Tangsubkul, N.; Beavis, P.; Moore, S.; Lundie, S.; Waite, T. Life Cycle Assessment of Water Recycling Technology. *Water Resour. Manag.* **2005**, *19*, 521–537.
7. Modahl, I.S.; Askham, C.; Lyng, K.-A.; Brekke, A. Weighting of environmental trade-offs in CCS—an LCA case study of electricity from a fossil gas power plant with post-combustion CO_2 capture, transport and storage. *Int. J. Life Cycle Assess.* **2012**, *17*, 932–943.
8. International Standard Organization. *ISO 14040:2006 Environmental Management-Life Cycle Assesment-Principles and Framework*; International Standard Organization: Geneva, Switzerland, 2006.
9. International Standard Organization. *ISO 14044:2006 Environmental Management-Life Cycle Assessment-Requirements and Guidelines*; International Standard Organization: Geneva, Switzerland, 2006.
10. Making a difference, Ecoinvent's global influence. Available online: http://www.ecoinvent.ch/ (accessed on 23 September 2014).
11. Goedkoop, M.; Oele, M.; Leijting, J.; Ponsioen, T.; Meijer, E. *SimaPro 8. Introduction to LCA with SimaPro*; PRé: Amersfoort, The Netherlands, 2013.
12. Guinée, J. *Handbook on Life Cycle Assessment: Operational Guide to the ISO Standards*; Kluwer Academic Publishers: Leiden, Netherlands, 2002.
13. Kellens, K.; Dewulf, W.; Overcash, M.; Hauschild, M.Z.; Duflou, J.R. Methodology for systematic analysis and improvement of manufacturing unit process life-cycle inventory (UPLCI)—CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 1: Methodology description. *Int. J. Life Cycle Assess.* **2012**, *17*, 69–78.
14. Kellens, K.; Dewulf, W.; Overcash, M.; Hauschild, M.Z.; Duflou, J.R. Methodology for systematic analysis and improvement of manufacturing unit process life cycle inventory (UPLCI) CO2PE! initiative (cooperative effort on process emissions in manufacturing). Part 2: case studies. *Int. J. Life Cycle Assess.* **2012**, *17*, 242–251.
15. Kellens, K.; Dewulf, W.; Lauwers, B.; Kruth, J.; Duflou, J. Environmental Impact Reduction in Discrete Manufacturing: Examples for Non-Conventional Processes. *Procedia CIRP* **2013**, *6*, 27–34.
16. Duflou, J.R.; Kellens, K.; Renaldi, R.; Guo, Y.; Dewulf, W. Critical comparison of methods to determine the energy input for discrete manufacturing processes. *CIRP Ann.-Manuf. Technol.* **2012**, *61*, 63–66.
17. Duflou, J.R.; Sutherland, J.W.; Dornfeld, D.; Herrmann, C.; Jeswiet, J.; Kara, S.; Hauschild, M.; Kellens, K. Towards energy and resource efficient manufacturing: A processes and systems approach. *CIRP Ann.-Manuf. Technol.* **2012**, *61*, 587–609.
18. PlasticsEurope. Plastics- the facts 2013, An analysis of European latest plastics production, demand and waste data. 2013. Available online: http://www.plasticseurope.org/documents/document/20131014095824-final_plastics_the_facts_2013_published_october2013.pdf (accessed on 20 March 2015).
19. Goedkoop, M.; Oele, M.; de Schryver, A.; Vieira, M. *SimaPro 7 Database Manual. Methods Library*; PRé: Amersfoort, The Netherlands, 2010.

20. Goedkoop, M.; Heijungs, R.; Huijbregts, M.; Strujis, J.; van Zelm, R. ReCiPe 2008 A life cycle impact assessment method which comprises harmonised category indicators at the midpoint and the endpoint level, Report I: Characterisation. 2009. Available online: http://www.leidenuniv.nl/cml/ssp/publications/recipe_characterisation.pdf (accessed on 20 March 2015).
21. Dong, Y.H.; Thomas, S. Comparing the midpoint and endpoint approaches based. *Int. J. Life Cycle Assess.* **2014**, *19*, 1409–1423.
22. Hischier, R. *Part II Plastics. Life Cycle Inventories of packaging and Graphical Papers. Ecoinvent-Report No.11*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
23. Boustead, I. Eco-Profiles of the European Plastics Industry. Polymer Conversion. Report 10; PlasticsEurope: Brussels, Belgium, 1997.
24. Habersatter, K.; Fecker, I.; Dall'Acqua, S.; Fawer, M.; Fallscheer, F.; Förster, R.; Maillefer, C.; Ménard, M.; Reusser, L.; Som, C.; *et al. Ökoinventare für Verpackungen*; BUWAL Schriftenreihe Umwelt Nr 250; Bern Bundesamt für Umwelt, Wald und Landschaft (BUWAL): Bern, Switzerland, 1998.
25. Hischier, R. *Part III Plastics. Life Cycle Inventories of packaging and Graphical Papers. Ecoinvent-Report No.11*; Swiss Centre for Life Cycle Inventories: Dübendorf, Switzerland, 2007.
26. Plastics Europe. *Eco-profiles of the European Plastics Industry. Injection Moulding of PVC, HDPE and PP*; Plastics Europe: Brussels, Belgium, 2010.

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Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts

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A B S T R A C T

This paper studies the environmental impact of the injection molding process by carrying out a life cycle assessment. A review of how EcoInvent's Life Cycle Inventory database characterizes this process has been conducted, and a new methodology based on that analysis has been carried out. Aspects such as the infrastructure of the factory or waste treatment are part of the environmental impact of the injection molding process, but the most significant factor is electricity consumption; therefore, electricity consumption measurements of the process have been performed. This environmental analysis has been applied to the processing of several parts made of high-density polyethylene, which have been characterized by measuring the electricity consumption. As a consequence of this work, it has been proven that electricity consumption can be used as an injection molding machine selection criteria, from an environmental standpoint, as it produces the highest environmental burden of the process.

1. Introduction

Today, plastics are one of the most used polyvalent materials and are an important part of the economy. They provide multiple applications in a wide range of sectors, from the packaging market, which represents 39.4% of the demand for plastics, to the building and construction sector, the automotive industry and other examples, such as home appliances or medical products (PlasticsEurope, 2013).

Among the different types of plastics, the three most demanded are the thermoplastic variations, polypropylene (PP), low-density polyethylene (LDPE) and high-density polyethylene (HDPE), according to (PlasticsEurope, 2013). The last one represents 12% of the total European plastic demand (PlasticsEurope, 2013). Injection molding is one of the most used plastic part manufacturing processes due to its precision and cost-effectiveness for large volume productions (Wang et al., 2013; Guevara-Morales and Figueroa-López, 2014). This process is divided into five phases: mold filling, packing, the simultaneously occurring cooling phase and plasticizing phase, and finally the ejection of the injected part. All of these phases make this process quite intensive, energetically speaking. Thus, that high electricity consumption also implies that the injection molding process is also relevant in terms of environmental impact, even more so bearing in mind the large scale of plastic parts manufacturing.

There are different types of injection molding machines depending on how the drives are powered: hydraulic, hybrid and all-electric. In the hydraulic type, the injection molding machine's motions are powered by hydraulic pumps. Today, almost no machinery is purely hydraulic as they typically use hybrid mechanisms, such as the toggle clamping mechanism that helps the hydraulic system and also provides electrical energy savings (Huang et al., 2011; Hsu et al., 2013). All-electric injection molding machines replace the hydraulic circuit with servomotors. One of the main specifications that characterize an injection molding machine is its clamping force, and this is related to the size of the parts that can be injected in it. There is a wide range of clamping forces, from micro-injection molding machines of approximately 50 kN of clamping force up to nearly 100,000 kN of clamping force (Muccio, 1994). In this paper, injection molding machines from 833 to 78,400 kN have been analyzed while manufacturing HDPE parts. This last injection molding machine is one of the largest operating in Spain.

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The plastics industry in Europe started to assess the environmental impact of plastics more than 20 years ago (Boustead, 1992). The societal concern regarding this subject is increasing around the world (Givens and Jorgenson, 2013), with the global warming threat as one of the primary reasons (Czap and Czap, 2010). This environmental concern has promoted the use and development of different methodologies that strive for sustainable development. The life cycle assessment (LCA) is a methodology used to calculate the environmental impact of products, processes or services. The results obtained by an LCA are analyzed so that priority areas in which actions should be applied can be identified (Guinée et al., 2002). Working in those areas allows researchers and designers to improve the environmental performance and, as a consequence, make products and processes more ecofriendly.

In the specific field of injection molding, Thiriez and Gutowski provide a review of the entire process, including the thermoplastic production, the compounding of the additives and the injection molding process (Thiriez and Gutowski, 2006). In that paper, the authors highlight the importance of the choice of the type of the injection molding machine as that could entail a high impact in the specific electricity consumption of the injection molding machine, therefore also influencing, as will be discussed in this paper, the environmental impact of the process. In the thesis of Almeida, a life cycle engineering task was performed, following a cradle-to-grave approach in order to determine the environmental performance of the injection molding of biodegradable plastics (Almeida, 2011). In the article written by Weissman et al., a methodology to estimate the electricity consumption of the injection of a molded part is explained, with the aim of providing an electricity consumption model to help designers make more environmentally conscious decisions (Weissman et al., 2010).

When performing an LCA of a product, the materials and manufacturing processes have to be identified. Among these processes, the injection molding process is usually included. Databases, such as EcoInvent, have defined the injection molding process based on measurements of several facilities at a European level (Hischier, 2007). In another report (TNO for Plastics Europe, 2010), PP and HDPE along with polyvinyl chloride (PVC), which are among the most demanded plastics, are used as a reference to characterize the environmental impact of the injection molding process.

These values could be used to incorporate them into the calculation of the environmental impact of that product as a first approach. However, if the level of detail required is higher or the injected parts are an important component of the study, this approach is not precise enough. As Gutowski et al. note in their research, the manufacturing process's electrical energy requirements are not independent of the characteristics of the manufactured parts, as the LCA databases traditionally assume (Gutowski and Thiriez, 2006).

The main aim of this essay is to analyze the different factors in the environmental impact of the injection molding process. From this analysis, a methodology is developed to calculate the environmental impact of a specific injection molding process, and it has been applied to several parts that use the same raw material (HDPE). The units of the obtained results will be per injected kilogram.

2. Materials and methods

In the following section, a review and analysis of the state of the art is going to be presented, as well as the equipment that has been used during this research, such as the raw material, molds and injection molding machines analyzed and the required measurement equipment.

2.1. State of the art review and analysis

Various authors have investigated the electrical energy requirements of plastics manufacturing processes. Muller et al. analyzed the injection molding by using dual electrical energy signatures to determine value- and non-value-adding elements to improve the process's efficiency by studying the influence of the process time and power levels on the injection molding machine (Müller et al., 2014).

Madan et al. also studied this process by considering its electricity consumption as an indicator of sustainability. They suggest that the LCAs performed today give much more importance to the material than to the manufacturing factors, and they propose a guideline to estimate the electricity consumption of UMPs (unit manufacturing processes), based on the analysis of the stages of the injection molding process, with the goal of benchmarking, evaluation and improvement (Madan et al., 2014).

Lucchetta and Bariani also conducted research based on this idea, suggesting that most LCE (Life Cycle Engineering) tasks, where the environmental and economic impact of the product are assessed simultaneously, are focused on minimizing the use of materials and increasing the recycled materials but do not take into account the cost and environmental impact of the manufacture of the design alternatives. They also remark on the importance that the injection molding industry has, in terms of environmental impact, due to its large scale (Lucchetta and Bariani, 2010). Yam and Mak studied the gas-assisted injection molding process. This process allows for the reduction of the use of petrochemical polymers and, at the same time, achieves electrical energy savings of 20% thanks to the reduction of processing parameters, such as the injection pressure and the clamping force of the injection molding machine (Yam and Mak, 2014).

The electrical energy demand has also been studied in other plastics manufacturing processes, such as polymer extrusion. For instance, Abeykoon et al. studied the electrical energy demand with different process conditions in order to optimize the process's efficiency (Abeykoon et al., 2014a). Alternately, Deng et al. presented a real-time electricity consumption monitoring method and used it to study the effect of process settings on melt quality and electrical energy efficiency, which are highly related with the electricity consumption (Deng et al., 2014). Moreover, results in other papers showed that the specific electrical energy demand was reduced as the throughput was increased (Abeykoon et al., 2014b). These experimental studies help to select operational conditions and equipment to optimize the process.

In this research, in order to analyze the environmental impact of the injection molding process, we have studied the injection molding dataset of EcoInvent v3.01 as a starting point (named in this paper as EcoI). To create the dataset for the generic injection molding process, EcoInvent calculates the arithmetic mean of data gathered from three average injection molding processes, PVC, PP and PET (Hischier, 2007), and correlates the inventory data to its own datasets. There are notable differences between input data of the different plastics.

To manufacture one kilogram of injected plastic parts, this inventory includes water used during this process, lubricating oil, and different types of additives, such as chemicals, solvents, pigments or fillers. It also considers packaging materials: pallets, polypropylene, LDPE and cardboard. The electricity, natural gas and other fuels are classified as energy inputs. The generated waste is separated into waste to landfill, hazardous waste and plastic waste from which energy is recovered by incineration.

Given that our raw material is going to be high-density polyethylene, we can use the report from which this database has been constructed (Hischier, 2007) and particularize it in order to obtain a more precise approach. Additionally, as the aim of this paper is to determine the environmental impact of the injection molding process for HDPE parts, the first step that has been carried out is to remove those values that do not directly belong to the injection molding process itself (Fig. 1), even though they may be necessary to deliver the final product. Therefore, packaging materials and the natural gas or other fuels used to heat the conversion plant are also not going to be considered, as those inputs are highly dependent on the part, factory, etc.

The second step performed in this study is to replace the remaining values with those of the polypropylene report, as this plastic is more similar to the HDPE from the three thermoplastics that EcoInvent uses to characterize its average injection molding process. This way, the dataset could be used to analyze most standard thermoplastics except for the PVC, which needs special treatment due to its chemical composition, as it has to be combined with several additives before processing (Pita et al., 2001). As we can see in the original data (Hischier, 2007), the PVC injection molding process has specific inputs, such as solvents or stabilizers, that are not used in conventional plastics and therefore are going to be omitted to analyze a standard thermoplastic, such as HDPE. Therefore, these elements would only be considered when PVC processing is the analyzed process.

Finally, EcoInvent's estimation of infrastructure of the plant and machinery is not modified. The following table (Table 1) shows the EcoInvent datasets that have been used in our particularized case for a standard thermoplastic, which is named in the text as CEcoIPP. The steps carried out to obtain this dataset are shown in Fig. 1.

As will be shown in the results section, the electricity consumption is the most influential element on the environmental impact, so the electricity consumption of our particular processes are going to be measured to obtain a more precise result.

The final dataset that will be used for the environmental impact of the HDPE parts is that achieved by the steps shown in Fig. 2. Fig. 3 shows, in a very schematic manner, the elements considered by EcoInvent and those left outside the system boundaries in our study. Emissions are considered as within the system boundaries, using the same methodology as EcoInvent. However, for the particularized case of CEcoIPP, their value is zero because there is no reported data for PP processing in the study (Hischier, 2007).

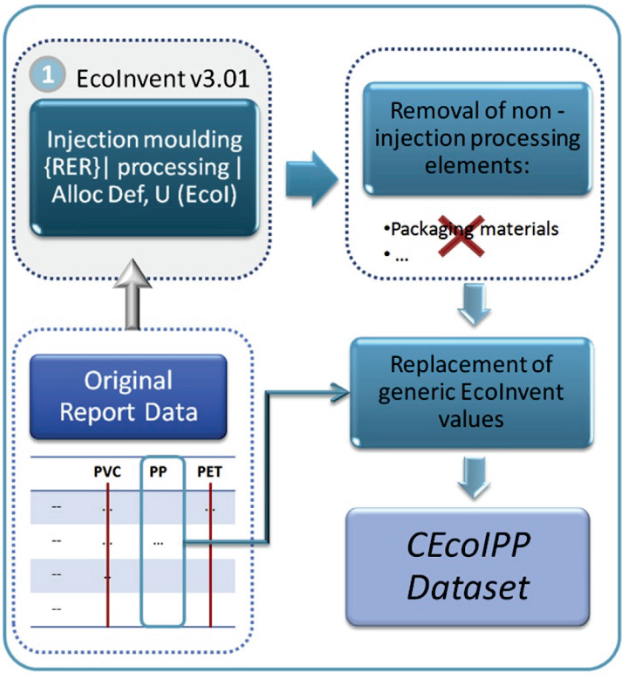

Fig. 1. Methodology steps performed to obtain the CEcoIPP dataset.

2.2. Required equipment

The required equipment consists of several injection molding machines (Table 2), HDPE as raw material, bascules to measure the weight of the part that is being injected during the experiment, a timer for measuring the cycle time, and a portable three-phase power analyzer, which measures the power that it is being used during the injection molding process by the injection molding machine and the auxiliary equipment.

The software used to perform LCA calculations is SimaPro 8.0.3.14 (Goedkoop et al., 2013), developed by Pré Consultants. The EcoInvent v3.01 database (Weidema et al., 2013) has been used as the main data source for the inventory.

2.2.1. Raw material

In all of the injection molding processes that have been measured, RIGIDEX 5740 UA HDPE has been used as the raw material.

Some of the properties of this raw material are:

- Density: 0.957 g/cm^3
- Melt Flow Index: 4 g/10 min
- Vicat softening: 125 °C
- Tensile yield strength: 27 MPa
- Flexural modulus: 1250 MPa

2.2.2. Molds and injection molding machines

Fig. 4 shows all of the HDPE parts for which processes have been measured.

Parts #1 and #2 are the bodies of two waste containers of different capacities, 2400 and 1000 L, respectively. Part #3 is a lid used for waste containers. Parts #4, #5 and #6 are both different-sized openings through which waste is inserted into the containers. Parts #7 and #8 are smaller parts from other containers. #7 is a shaft that connects to and allows the rotation of a lid on the body container, and part #8 is a plug whose task is to cover some of the container's elements.

All of these parts have been injected in several injection molding machines, which are classified in Table 2, based on their clamping force. All of them are hybrids, except for the 833 kN one, which is an all-electric injection molding machine. Some images of the measured injection molding machines are shown in Figs. 5–7.

2.2.3. Measurement equipment

This equipment (Fig. 8) is formed by a Circutor C-80 power analyzer that records the measurements and other accessories, which include several clamps that measure the current, voltage cables with crocodile clamps that are connected to the electric panel to measure voltage, and, finally, rubber gloves to ensure safety when connecting the devices to the grid.

For this study, three different current clamps have been used, and each one of them is adequate for an interval of electric current. In Fig. 8, the power analyzer connected to the electrical panel is shown. In this manner, the C-80 power analyzer registers the average power consumed by the injection molding machine and all auxiliary equipment. The accuracy for the power rating of the instrument is 1%, which is precise enough for these measurements; differences between measurements are much larger than the

Table 1
EcoInvent's Dataset, used to particularize the case.

Description	EcoInvent v3.01 dataset	Customized EcoInvent based PP injection molding process values (CEcoIPP)
Lubricants	Lubricating oil {GLO}| market for | Alloc Def, U	1.67E-05 kg
Water for cooling	Water, cooling, unspecified natural origin	1.11E-02 m^3
Electricity	Electricity, medium voltage market for | Alloc Def, U	2.096 kWh
Plastic waste	Waste plastic, mixture {GLO}| market for | Alloc Def, U	0.005 kg
Infrastructure	Packaging box factory {GLO}| market for | Alloc Def, U	1.43E-09 p

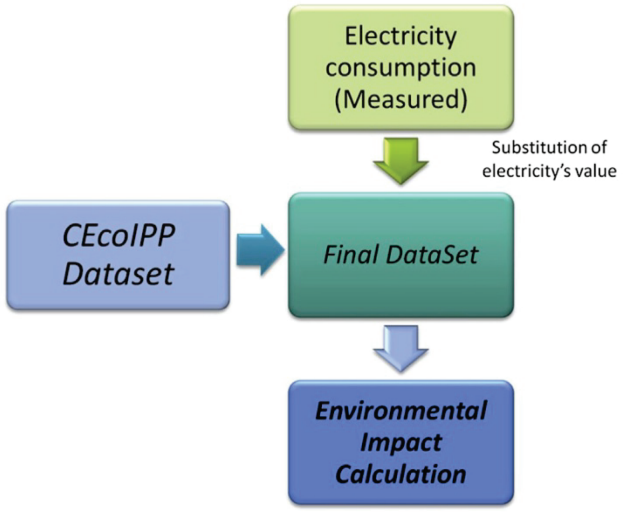

Fig. 2. Final dataset.

accuracy of the instrument, so the conclusions drawn from them will not be affected by the precision of the instrument.

2.3. Measurement procedure

Before a measurement begins, the maximum instantaneous current measured by the power analyzer must be checked in order to decide the most suitable current clamp. It is advised by the analyzer's manufacturer to measure in the highest part of the scale for better accuracy. Additionally, it is important that the production is stable during the test so that measurements will not take place during start-up periods. If production stops during the test, the measurement is discarded. The duration of the test with this sampling period is at least three hours. This provides enough data to check and ensure that the production is stable.

To calculate the kWh/kg of the injection molding process, the plastic weight processed per cycle, the cycle time and the measured power of the equipment are obtained. To determine if the measurement value is representative, it is recommended to use a spreadsheet to analyze the gathered data to ensure that the electricity consumption value is stable.

3. Life Cycle Inventory, LCI

According to the methodology explained before, the inventory of our injected molding process will be the dataset collected in

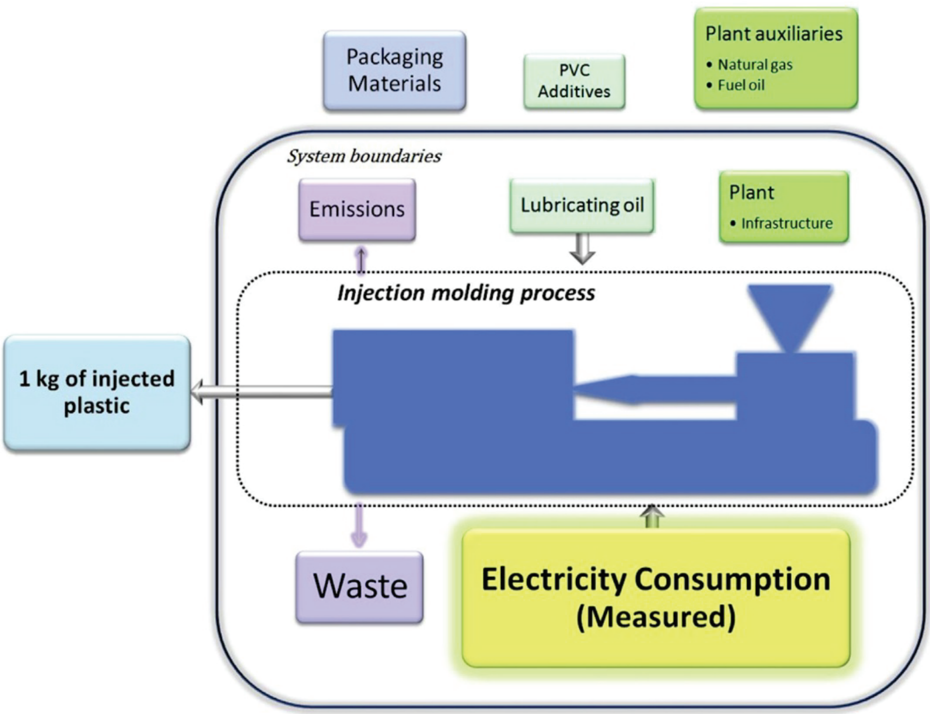

Fig. 3. System Boundaries of our particularized injection molding process.

Table 2
Injection molding machines in which parts have been injected.

Injection molding machine	Clamping force [kN]	Injected Part#	Type
A	78,400	1	Hybrid
B	50,960	2	Hybrid
C	29,400	3	Hybrid
D	11,760	4	Hybrid
E	7350	5 and 6	Hybrid
F	3920	7	Hybrid
G	833	8	All-electric

Table 1, but the electricity is replaced by the kWh/kg value obtained by our process measurement. EcoInvent's European electrical mix is used.

3.1. Life cycle impact assessment, LCIA

To assess the environmental impact, there are two possible ways of calculating the results: midpoint and endpoint. To avoid the subjectivity of the endpoint approach, methodologies such as CML Leiden, which uses a midpoint approach, can be used (Guinée et al., 2002). The CML Leiden method is recognized as one of the most widely used in LCA studies (Wäger et al., 2011) (Monteiro and Freire, 2012).

For these reasons, the results are calculated with the CML Leiden methodology, which computes the environmental impact in all categories of CML: abiotic depletion, abiotic depletion (fossil fuels), global warming (GWP 100), ozone layer depletion (ODP), human toxicity, fresh water aquatic ecotoxicity, marine aquatic ecotoxicity, terrestrial ecotoxicity, photochemical oxidation, acidification and eutrophication.

A detailed explanation of these categories can be referred to in guides such as (Guinée et al., 2002).

3.2. Measured electricity consumptions

In Table 3, the injected weight per cycle is collected, along with its cycle time and the electricity consumption.

There are significant differences between the measured parts. Part #1 consumes less electricity per kilogram with 0.431 kWh/kg, and part #5 has the highest electricity consumption at 2.31 kWh/kg. These results show that the electricity consumptions fluctuate significantly for different parts and injection molding machines. Many of the measurement values are lower than EcoI's average value of 1.47 kWh/kg or the 2.096 kWh/kg reported by (Hischier, 2007) for PP processing (CEcoIPP).

Although there are differences, such as the type of injection molding machine or the geometry, that also have an influence, a clear tendency is observed: parts with high throughput (Kg/h) usually have less electricity consumption per injected kilogram, a tendency that has also been observed by other authors, such as Thiriez and Gutowski for the injection molding process (Thiriez and Gutowski, 2006) and Abeykoon et al. in the extrusion of polymers (Abeykoon et al., 2014a,b).

For example, it is interesting to analyze the differences between the electricity consumption per kilogram of part #5 and part #6. These parts were both injected in the same injection molding

Fig. 4. Parts for which the processing has been measured.

Fig. 5. 78400-kN injection molding machine A.

Fig. 6. 29400-kN injection molding machine C.

machine (Injection Molding Machine E, Clamping force: 7350 kN) and have similar cycle times. However, the weight of part #6 is more than three times larger than that part #5, and, conversely, its electricity consumption per kilogram is more than three times lower than that of part #5.

4. Results and discussions

Results for the EcoInvent Dataset, the customized dataset CEcoIPP, and the HDPE injected parts are going to be shown and discussed in this section. Several tables collect the environmental impact results in CML units. Graphics will represent the percentage of the elements of the inventory for each impact category, and a final figure will compare all of the different results.

4.1. EcoInvent dataset results (EcoI)

Table 4 shows the total results for the Injection moulding (RER) process of the EcoInvent v3.01 database.

Fig. 9 summarizes the contribution of the different elements associated with the injection molding process for each impact category.

In these generic results obtained with the LCI values of the EcoInvent database, the electricity is the most important factor in all of the impact categories, except for the abiotic depletion where the infrastructure has more importance (43.6%) due to the kilograms of steel that is considered for the factory's machinery.

Additives, including solvents and stabilizers, specific to PVC processing are also a significant part of the environmental burden,

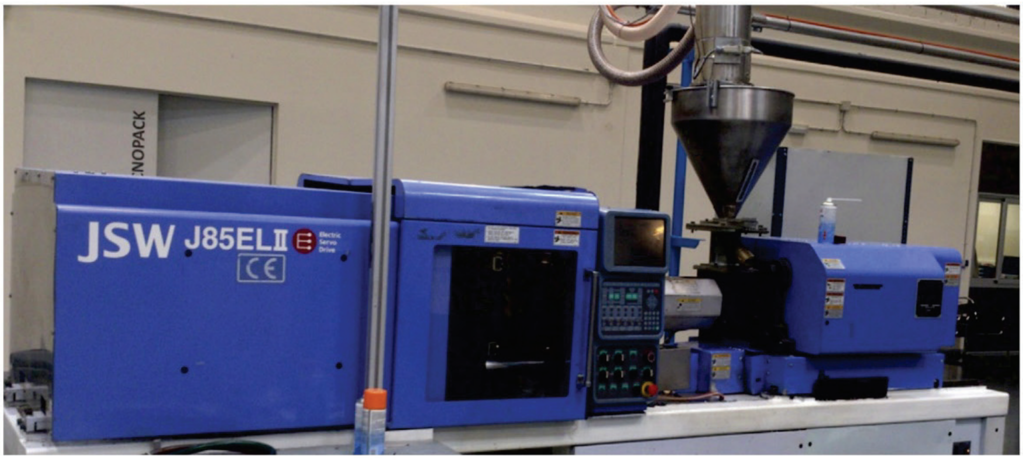

Fig. 7. 833-kN all-electric injection molding machine G.

Fig. 8. Measurement equipment.

especially in the photochemical oxidation (33%) and ozone layer depletion (18%) impact categories. Other energy inputs, such as natural gas and other fuels, also contribute notably to the depletion of fossil fuels, the ozone layer depletion and the global warming potential (approximately 15%).

Table 3
Data of the measured parts.

Part#	Weigh injected per cycle [g]	Cycle time [s]	Electricity consumption [kWh/kg]
1	71,800	216.0	0.4310
2	30,300	147.0	0.7878
3	10,500	175.0	0.8832
4	1253	81.0	0.9005
5	260	42.9	2.3007
6	836	40.0	0.7088
7	100	44.4	1.8699
8	15	15.0	0.6101

4.2. Customized dataset result (CEcoIPP)

The results of our modified EcoInvent dataset for analyzing the injection molding process of a conventional thermoplastic are shown in Table 5.

In our customized process (CEcoIPP, Table 1), where specific PVC additives have been removed, along with packaging materials and fuels, the electricity consumed by the injection molding process accounts for more than 94% of the environmental impact in almost every impact category, except for the first one (Table 5), similarly to the EcoI results.

This fact justifies the required equipment and the measurement procedure shown in subsection 2.3. By measuring the electrical consumption of our process, its environmental impact can be calculated in a very accurate way.

Table 6 shows a comparison between the EcoI and the CEcoIPP results. These values can be better understood by taking into

Table 4
EcoInvent v3.01 (EcoI) results.

Impact category	Unit	Environmental impact per kg of processed material
Abiotic depletion	kg Sb eq	1.428E-06
Abiotic depletion (fossil fuels)	MJ	1.887E+01
Global warming (GWP100a)	kg CO_2 eq	1.094E+00
Ozone layer depletion (ODP)	kg CFC-11 eq	1.254E-07
Human toxicity	kg 1,4-DB eq	3.768E-01
Fresh water aquatic ecotox.	kg 1,4-DB eq	4.197E-01
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.333E+03
Terrestrial ecotoxicity	kg 1,4-DB eq	2.537E-03
Photochemical oxidation	kg C_2H_4 eq	2.940E-04
Acidification	kg SO_2 eq	4.545E-03
Eutrophication	kg PO_4 eq	2.250E-03

account the higher value of electricity consumption for the CEcoIPP (+42.6% over the average electricity consumption of the EcoI dataset) and also the exclusion of inventory data as explained in Section 2.1.

Some categories, such as both abiotic depletion categories, ODP and photochemical oxidation, show a lower impact on the ecological environment due to the removals explained in Section 2.1 (solvents, stabilizers, natural gas, etc.). Alternately, for those categories in which the contribution of the electricity consumption is high (Fig. 9), such as human toxicity, all of the ecotoxicity categories, and eutrophication, there is a relevant impact increase.

4.3. HDPE parts results and comparison

In Table 7, the environmental impact of the customized process with the polypropylene values (CEcoIPP) is compared with the results for each measured part.

In Fig. 10, it can be seen how the differences between parts in each impact category follow the same proportion the electricity

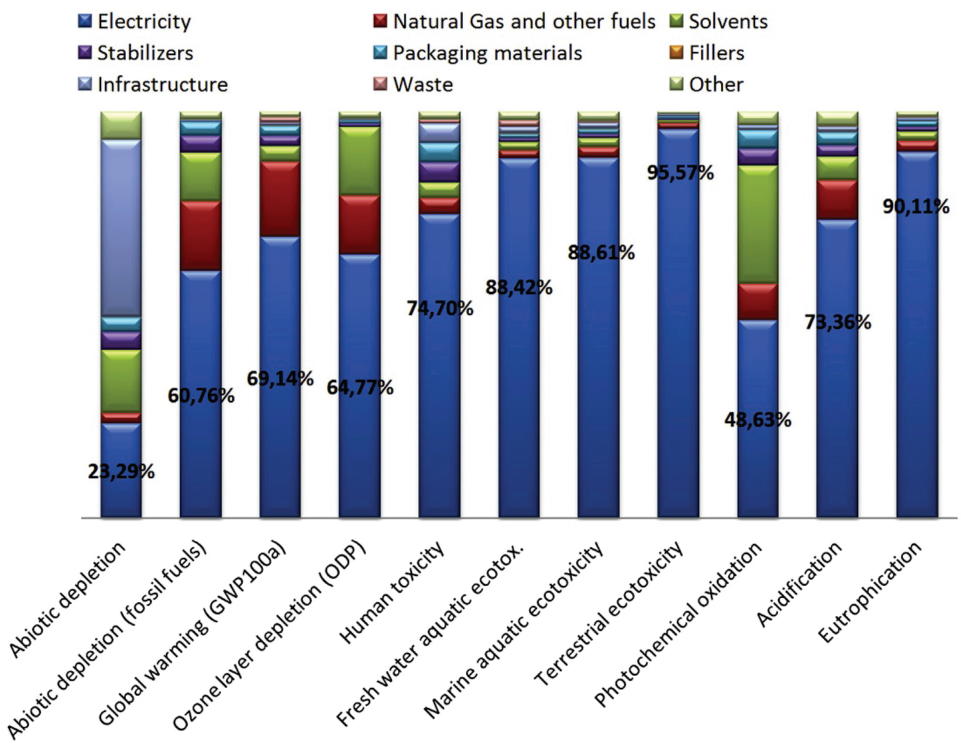

Fig. 9. Impact results for each impact category (EcoI).

Table 5
Particularized case (CEcoIPP) results.

Impact category	Unit	Environmental impact per kg of processed material	% Electricity
Abiotic depletion	kg Sb eq	1.10E-06	43.02%
Abiotic depletion (fossil fuels)	MJ	1.63E+01	99.37%
Global warming (GWP100a)	kg CO_2 eq	1.09E+00	98.17%
Ozone layer depletion (ODP)	kg CFC-11 eq	1.15E-07	99.64%
Human toxicity	kg 1,4-DB eq	4.20E-01	94.91%
Fresh water aquatic ecotox.	kg 1,4-DB eq	5.37E-01	97.83%
Marine aquatic ecotoxicity	kg 1,4-DB eq	1.70E+03	98.58%
Terrestrial ecotoxicity	kg 1,4-DB eq	3.45E-03	99.53%
Photochemical oxidation	kg C_2H_4 eq	2.06E-04	98.38%
Acidification	kg SO_2 eq	4.78E-03	98.69%
Eutrophication	kg PO_4 eq	2.89E-03	99.31%

Table 6
Comparison between the EcoI and CEcoIPP results.

Impact category	EcoI	CEcoIPP
Abiotic depletion	100.0%	77.0%
Abiotic depletion (fossil fuels)	100.0%	86.4%
Global warming (GWP100a)	100.0%	99.6%
Ozone layer depletion (ODP)	100.0%	91.7%
Human toxicity	100.0%	111.5%
Fresh water aquatic ecotox.	100.0%	127.9%
Marine aquatic ecotoxicity	100.0%	127.5%
Terrestrial ecotoxicity	100.0%	136.0%
Photochemical oxidation	100.0%	70.1%
Acidification	100.0%	105.2%
Eutrophication	100.0%	128.4%

consumption does. Only in the abiotic depletion category are the differences smaller. As has been seen in a previous subsection (4.2 Customized Dataset result (CEcoIPP)), the infrastructure is the most influential element in the abiotic depletion category, and this element was kept constant in the LCI in all cases. Despite this, the electricity also has an influence in this impact category, as is indicated in Table 5 (43% in CEcoIPP results, compared to infrastructure with 56.87%).

Thus, the final results show that there is a great variation due to the electricity contribution. Part #1 involves the lowest environmental impact per kilogram because its electricity consumption is the lowest of the measured parts. Alternately, the processing of one kilogram of part #5 creates an even higher impact than the calculated CEcoIPP due to its electricity consumption of 2.31 kWh/kg.

In view of the results shown in this paper, the results and conclusions of LCA studies that use EcoInvent data for the injection molding process may slightly differ, especially if this process is important for the studied product. For example, consider the study carried out by Rives et al., where a comparison between different systems for municipal solid waste management was made. In that research, the environmental impact of several HDPE containers with different capacities was assessed using the injection molding data of EcoInvent and compared with other steel alternatives. Based on our data, the environmental impact of the injection molding process of these containers, some of them similar to parts

Table 7
Results comparison.

Impact category	CEcoIPP	#1	#2	#3	#4	#5	#6	#7	#8
Abiotic depletion	100.0%	65.5%	72.8%	74.8%	75.1%	103.7%	71.2%	94.9%	69.2%
Abiotic depletion (fossil fuels)	100.0%	21.1%	38.1%	42.6%	43.4%	110.0%	34.3%	89.5%	29.6%
Global warming (GWP100a)	100.0%	22.1%	38.8%	43.3%	44.1%	109.7%	35.1%	89.5%	30.5%
Ozone layer depletion (ODP)	100.0%	20.9%	37.9%	42.5%	43.3%	110.1%	34.2%	89.6%	29.5%
Human toxicity	100.0%	24.6%	40.8%	45.1%	45.9%	109.3%	37.2%	89.8%	32.7%
Fresh water aquatic ecotox.	100.0%	22.3%	39.0%	43.4%	44.2%	109.6%	35.3%	89.5%	30.7%
Marine aquatic ecotoxicity	100.0%	21.7%	38.4%	42.9%	43.7%	109.4%	34.7%	89.2%	30.1%
Terrestrial ecotoxicity	100.0%	20.9%	37.9%	42.4%	43.2%	109.7%	34.1%	89.3%	29.4%
Photochemical oxidation	100.0%	21.8%	38.6%	43.0%	43.9%	109.5%	34.9%	89.3%	30.2%
Acidification	100.0%	21.6%	38.4%	42.9%	43.8%	109.7%	34.7%	89.4%	30.1%
Eutrophication	100.0%	21.1%	38.0%	42.6%	43.4%	109.7%	34.3%	89.3%	29.6%

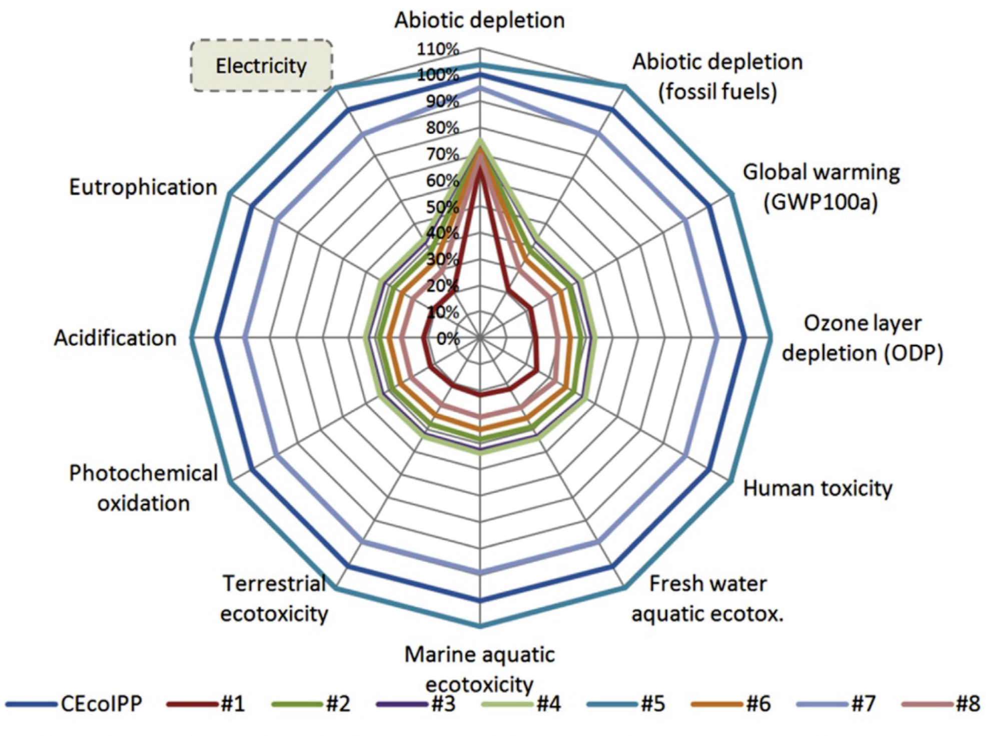

Fig. 10. Comparison between CEcoIPP and the measured parts for every impact category and for electricity consumption.

#1 and #2, may be lower, but, in this case, it would not affect the overall conclusions as the studied steel containers produce significantly lower environmental impact than the HDPE ones (Rives et al., 2010).

Pina et al. presented the LCA of several induction hobs (Pina et al., 2015). The inventories showed several injection molded parts (of PA66, PPS, ABS). In their results, injection molding had a noteworthy impact, so a detailed study of the injection molding process for those parts would be necessary to improve the precision of that study, as injected parts were assessed with the injection molding dataset of EcoInvent. The authors already warned that the impacts of the injection molding process are high due to the presence of solvents in the EcoInvent dataset, which specially influences the results of the ozone layer depletion. Some other examples of studies where EcoInvent's injection molding dataset is used are LCAs of agricultural machinery (Bortolini et al., 2014), road lighting luminaires (Tähkämö and Halonen, 2015) and fuel cells (Cox and Treye, 2015). The injection molding process should be studied in detail and measured in all LCA studies where plastic components are a significant part of the product.

5. Conclusions

Throughout this study, the environmental impact of the injection molding process has been analyzed. A methodology and experimental measurement procedure have been explained and applied to a wide range of HDPE plastic parts.

The generic EcoInvent dataset (EcoI) and our adapted case to analyze the injection molding of conventional plastics (CEcoIPP) yield similar environmental burdens. Finally, the measured parts' environmental results exhibited significant differences. This is due to electricity consumption differences, ranging from 0.43 kWh/kg to 2.3 kWh/kg.

To properly assess the actual environmental impact of a specific injection molding process, the real electricity consumption of it must be measured. Otherwise, the results would be quite far from the real values.

6. Future directions of research

Additionally, this paper opens a future direction of research, investigating how the electricity consumption of the injection molding machine can be optimized by means of a better machine selection. Additionally, differences between materials and the influence of the part characteristics could be assessed.

Electricity consumption should be used as a selection criterion of injection molding machines to develop a more environmentally conscious way of manufacturing injected plastic parts and simultaneously reducing production costs.

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References

Abeykoon, C., Kelly, A.L., Brown, E.C., Vera-Sorroche, J., Coates, P.D., Harkin-Jones, E., Price, M., 2014a. Investigation of the process energy demand in polymer extrusion: a brief review and an experimental study. Appl. Energy 136, 726–737.

Abeykoon, C., Kelly, A.L., Vera-Sorroche, J., Brown, E.C., Coates, P.D., Deng, J., Price, M., 2014b. Process efficiency in polymer extrusion: correlation between the energy demand and melt thermal stability. Appl. Energy 135, 560–571.

Almeida, D.N., 2011. Life Cycle Engineering Approach to Analyze the Performance of Biogradable Injection Moulding Plastics. Instituto Superior Técnico, Universidade Técnica de Lisboa.

Bortolini, M., Cascini, A., Gamberi, M., Mora, C., Regattieri, A., 2014. Sustainable design and life cycle assessment of an innovative multi-functional haymaking agricultural machinery. J. Clean. Prod. 82, 23–36.

Boustead, I., 1992. Eco-balance Methodology for Commodity Thermoplastics. The European Centre for Plastics in the Environment (PWMI). Later Association of Plastics Manufacturers in Europe (APME), Brussels.

Cox, B., Treye, K., 2015. Environmental and economic assessment of a cracked ammonia fuelled alkaline fuel cell for off-grid power applications. J. Power Sources 275, 322–335.

Czap, N., Czap, H.J., 2010. An experimental investigation of revealed environmental concern. Ecol. Econ. 69, 2033–2041.

Deng, J., Li, K., Harkin-Jones, E., Price, M., Karnachi, N., Kelly, A., Fei, M., 2014. Energy monitoring and quality control of a single screw extruder. Appl. Energy 113, 1775–1785.

Givens, J.E., Jorgenson, A.K., 2013. Individual environmental concern in the world polity: a multilevel analysis. Soc. Sci. Res. 42, 418–431.

Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., Meijer, E., 2013. SimaPro 8. Introduction to LCA with SimaPro, PRé. Amersfoort.

Guevara-Morales, A., Figueroa-López, U., 2014. Residual stresses in injection molded products. J. Mater. Sci. 49, 4399–4415.

Guinée, J., Gorrée, M., Heijungs, R., Huppes, G., Kleijn, R., Koning, A., Huijbregts, M., 2002. Handbook on Life Cycle Assessment. Operational Guide to the ISO Standards. Part III: Scientific Background. Kluwer Academic Publishers, Dordrecht.

Gutowski, T.D., Thiriez, 2006. Electrical energy requirements for manufacturing processes. In: 13th CIRP International Conference of Life Cycle Engineering. Lueven.

Hischier, R., 2007. Part II Plastics. Life Cycle Inventories of Packaging and Graphical Papers. Ecoinvent-report No.11. Swiss Centre for Life Cycle Inventories, Dübendorf.

Hsu, Y.-L., Huang, M.-S., Fung, R.-F., 2013. Energy-saving trajectory planning for a toggle mechanism driven by a PMSM. Mechatronics 24, 23–31.

Huang, M.-S., Lin, T.-Y., Fung, R.-F., 2011. Key design parameters and optimal design of a five-point double-toggle clamping mechanism. Appl. Math. Model. 35, 4304–4320.

Lucchetta, G., Bariani, P., 2010. Sustainable design of injection moulded parts by material intensity reduction. CIRP Ann. Manuf. Technol. 59, 33–36.

Madan, J., Mani, M., Lee, J.H., Lyons, K.W., 2015. Energy performance evaluation and improvement of unit-manufacturing processes: injection molding case study. J. Clean. Prod. 105, 157–170.

Monteiro, H., Freire, F., 2012. Life-cycle assessment of a house with alternative exterior walls: comparison of three impact assessment methods. Energy Build. 47, 572–583.

Muccio, E.A., 1994. Plastics Proccessing Technology. ASM International, Materials Park, Ohio.

Müller, E., Schillig, R., Stock, T., Schmeiler, M., 2014. Improvement of injection moulding processes by using dual energy signatures. Procedia CIRP 17, 704–709.

Pina, C., Elduque, D., Javierre, C., Martínez, E., Jiménez, E., 2015. Influence of mechanical design on the evolution of the environmental impact of an induction hob. Int. J. Life. Cycle Assess. http://dx.doi.org/10.1007/s11367-015-0890-y.

Pita, V., Sampaio, E., Monteiro, E., 2001. Mechanical properties evaluation of PVC/plasticizers and PVC/thermoplastic polyurethane blends from extrusion processing. Polym. Test. 21, 545–550.

PlasticsEurope, 2013. Plastics – the Facts 2013, an Analysis of European Latest Plastics Production, Demand and Waste Data. Brussels.

Rives, J., Rieradevall, J., Gabarrell, X., 2010. LCA comparison of container systems in municipal solid waste management. Waste Manag. 30, 949–957.

Tähkämö, L., Halonen, L., 2015. Life cycle assessment of road lighting luminaires – comparison of light-emitting diode and high-pressure sodium technologies. J. Clean. Prod. 93, 234–242.

Thiriez, A., Gutowski, T., 2006. An Environmental Analysis of Injection Molding. Massachusetts Institute of Technology, Cambridge.

TNO for Plastics Europe, 2010. Eco-profiles of the European Plastics Industry. Injection Moulding of PVC, HDPE and PP. Plastics Europe.

Wäger, P., Hischier, R., Eugster, M., 2011. Environmental impacts of the Swiss collection and recovery systems for Waste Electrical and Electronic Equipment (WEEE): a follow-up. Sci. Total. Environ. 409, 1746–1756.

Wang, H., Wang, Y., Wang, Y., 2013. Cost estimation of plastic injection molding parts through integration of PSO and BP neural network. Expert Syst. Appl. 40, 418–428.

Weidema, B.P., Bauer, C., Hischier, R., Mutel, C., Nemecek, T., Reinhard, J., Wernet, G., 2013. Overview and Methodology. Data Quality Guideline for the Ecoinvent Database Version 3. Ecoinvent Report 1 (v3). Swiss Centre for Life Cycle Inventories, The Ecoinvent Centre. St. Gallen, Switzerland.

Weissman, A., Gupta, S.K., Ananthanarayanan, Sriram, R.D., 2010. A Systematic Methodology for Accurate Design-state Estimation of Energy Consumption for Injected Molded Parts. Montreal,Quebec.

Yam, R., Mak, D., 2014. A cleaner production of rice husk-blended polypropylene ecocomposite by gas-assisted injection moulding. J. Clean. Prod. 67, 277–284.

9.3. EMSS 2015: LCA Software for Environ. Impact Assess. of Injected Mould Plastic Parts

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LCA SOFTWARE FOR ENVIRONMENTAL IMPACT ASSESMENT OF INJECTED MOULDED PLASTIC PARTS

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ABSTRACT

A software for the simulation of the environmental impact of injected moulded plastic parts is presented in this paper. The LCA model and assumptions made for calculations are explained, and the software's interface is shown. A case study is carried out in order to provide a clearer explanation of the applicability of this environmental impact simulation software. Results show how the raw material is the most influential factor. In second position is the injection moulding process, which has been modelled in detail, depending on many parameters.

Keywords: environmental impact simulation, software, life cycle assessment, injection moulding

1. INTRODUCTION

A more environmental benign manufacturing is an important goal for all industrial companies nowadays. As pointed out by (Duflou et al. 2012), a more demanding environmental legislation (European Parliament 2009), achieving cost savings thanks to more efficient technologies, or competitive advantages, should be important reasons to motivate a movement towards sustainability.

During the last decades, simulation tools have been developed in order to evaluate the environmental performance of products and processes. One of the most important methodologies to achieve that is the Life Cycle Assessment. There are numerous examples of this methodology where the environmental performance of different kind of products or processes is simulated. Studies like the ones performed by (Martínez et al. 2009), (Cellura et al. 2012), (Ribeiro et al. 2013a), (Jiménez et al. 2014), (Elduque et al. 2014b), (Tsiropoulos et al. 2015), (Martínez et al. 2015), (Wäger and Hischier 2015) and (Simon et al. 2015) are some examples of them.

Plastics manufacturing is one of the most important industrial manufacturing processes worldwide.

Several authors have analyzed this process, trying to improve its efficiency by means of design of experiments (Packianather et al. 2013) or software simulation. Also calculating its environmental impact in detail is an issue that is being addressed in other researches (Elduque et al. 2015).

In this paper a software simulation tool to perform the LCA of an injected moulded part is presented.

When a LCA is carried out, all the life stages of the product have to be taken into account in the model. Thereby, the production of the polymer, distribution of the raw material to the manufacturing company, the usage of auxiliary equipment and the injection moulding process itself should be included in the simulation. Also packaging materials used to deliver the product to the client, its distribution and its end-of life should be considered, as well as the waste generated throughout the life cycle, (Figure 1).

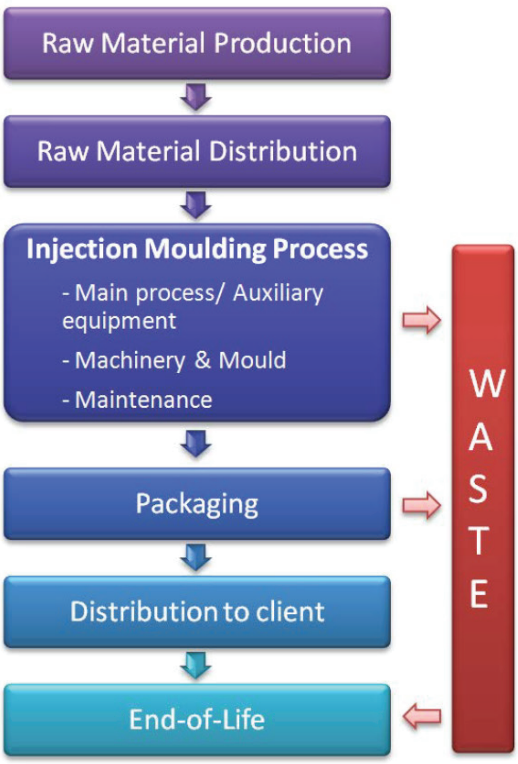

Figure 1: Life Cycle Stages of an Injected Moulded Part

This is a relevant research topic as a wide range of authors have analyzed the energy efficiency of this process to reduce it (Gutowski et al. 2006), (Borchardt et al. 2011), (Huang and Yang 2012), (Madan et al. 2014), (Müller et al. 2014), (Spiering et al. 2015) whereas others have analyzed the Life Cycle Cost of injection moulding (Ribeiro et al. 2013b). Also, several researchers have tried to reduce the impact of plastic parts (Lucchetta and Bariani 2010), (Park et al. 2013).
Simulations tools have been widely used to improve injection moulding (Gerber et al. 2006), (Aisa et al. 2006), (Jimenez et al. 2009), (Fernandez et al. 2013).
A streamlined environmental impact simulation tool based on an a LCA model, that takes into account all the relevant factors related to the process of manufacturing an injected moulded plastic part, is presented in this paper.

2. SOFTWARE DEVELOPMENT AND LCA MODELLING IMPLEMENTATION

This LCA software has been developed using Visual Basic .NET having a very clear structure. It has three main blocks: databases used as inputs to the environmental impact simulation model, user interface, where input data are introduced by the user throughout several screens to characterize the studied part and results are displayed and, at last, the software's code which acts as a black box for the user. The input data are processed, saving it in variables, which interoperate and return the simulation results that are then displayed in the interface.
In subsection 2.2, the program's screens are going to be described as well as the internal assumptions that are behind them to simulate the environmental impact of the considered blocks.
In order to help the user during the data introduction, multiple guides and suggestions are included in the software's interface.

2.1. Databases

In order to simulate the environmental impact results of an injected moulded plastic part, several databases have been developed. One of them contains the inventory datasets and their environmental impact calculated in mPt (ReCiPe Methodology) and kilograms of CO_2 eq. Aspects like the electric mix, lubricating oil, materials such as polymers for the injection moulding, metals for the mould, packaging materials...etc. are included. These values have been obtained from EcoInvent database.
Other databases contain properties of materials, or data related to required equipment for the process that the program uses, for example, to simulate the energy consumption.

2.2. Software Methodology

Software interface is divided into different screens where required data can be introduced by the user or selected between different modelling options provided by the software.

A summarized flux diagram of the software is shown in Figure 2.

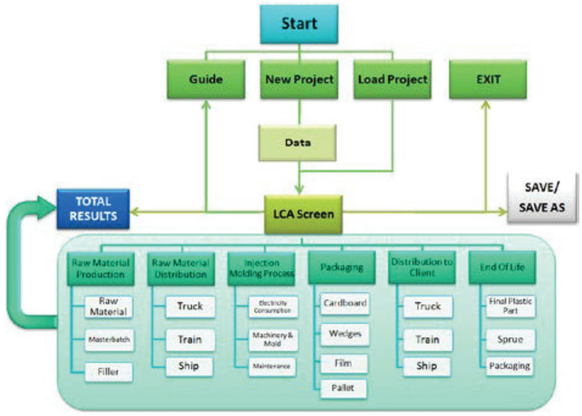

Figure 2: Software's Flux Diagram

Data regarding the part's net weight, the mould's feeding system and the number of the mould's cavities are required at the start of the modelling case study, in order to determine the quantity of sprue associated with the final part.This sprue could be assessed separately at the end-of-life phase. For example a mould without cold runners and one cavity hasn't got any sprue, but a plastic part obtained from a multy-cavity mould with a cold runner feeding system, will have associated the proportion of the runner also as used material. In addition, the total of kilograms injected to obtain the moulded part are calculated, as the section of the injection molding process simulates the environmental impact per processed kilogram.
Figure 3 shows the main LCA screen of the program which allows to go to the input data screen of each phase of the plastic part's life cycle.

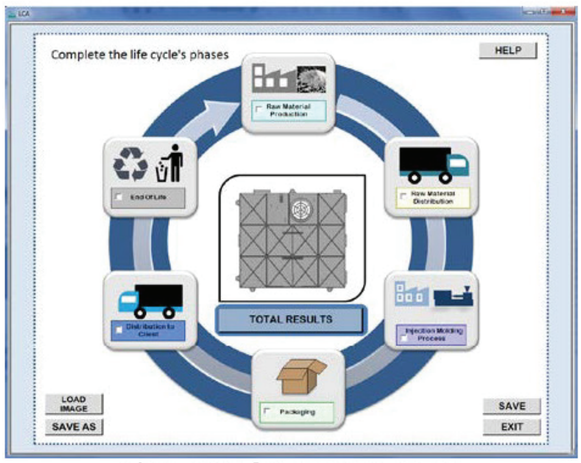

Figure 3: Software's LCA Screen

Environmental impact results are displayed in each section to check how the input data affect the results but also a "Total Results" screen has been developed to compare which life cycle phases have more importance in the ReCiPe Methodology and the carbon footprint (kg CO_2 equivalent).

2.2.1. Raw Material Production

The first phase of the LCA model for an injected moulded part is the raw material production. The database provides the environmental impact of materials obtained from professional Life Cycle Inventory databases such as EcoInvent. In addition, if the user wants to incorporate a new raw material, a mix of thermoplastic polymer, masterbatch and fillers can be modelled to better evaluate the environmental impact of the part's material.

2.2.2. Raw Material Distribution

The raw material is then distributed to the conversion's factory. A transport route can be configured using either road, rail or marine transport. The environmental impact's unit for this section is kg.km and the transported weight corresponds to the part's gross weight. An extra weight can be added if sacks or boxes are considered for the modelling of this phase.

2.2.3. Injection Moulding Process

The most important part of the program is the section where the environmental impact of the process is modelled.

Energy consumption is simulated as a sum of individual electric consumptions like the heating of the barrel, the hot runners if they are used, pneumatic or conveyor systems, dryers, coolers, and the drivers of the injection moulding machine. If known, it is possible to introduce experimental power measurements of the machine, in order to have a more precise model and therefore more adequate simulation results (Figure 4).

If it is not possible to introduce experimental measurements, a simulation of the energy consumption can be done. Energy consumption is modelled as a sum of six blocks:

- Plastification: the required energy is approximated as the specific heat of the thermoplastic material multiplied by the difference between injection temperature and factory's temperature, and divided by an assumed barrel's yield value.
- Hot runner: two options have been considered for the model. First one is to consider its energy consumption as a percentage of the plastification phase. The other one provides a power value (in kW) of typical equipment and a usage factor that usually is 50% (Thiriez 2006).
- Conveying system: manufacturer's specifications from several equipments of different power's level are provided. The user can select between different modelling options and indicate if the equipment's working point is optimum, in average load or over-sized. A value of consumption is returned depending on the selection. This value was obtained as an arithmetic mean of the different working points.

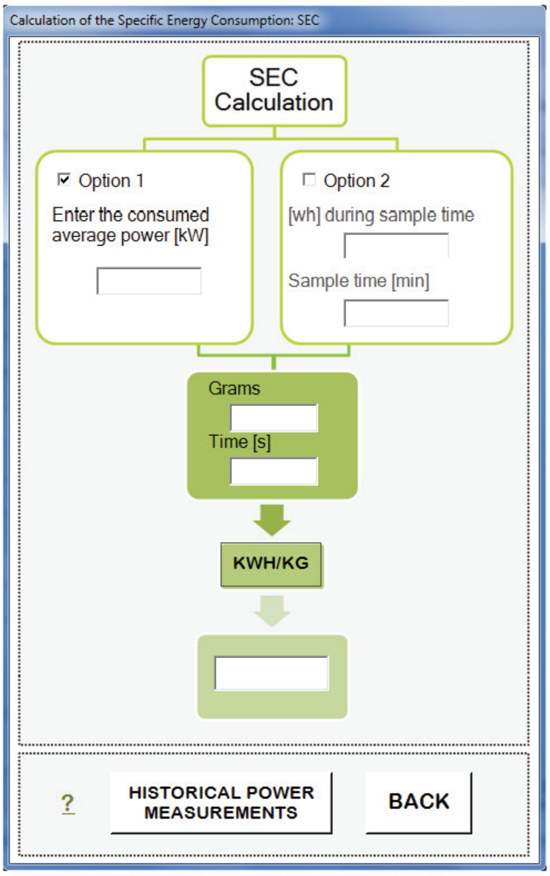

Figure 4: Specific Energy Consumption Calculator

- Dryer: as in other phases two alternatives can be selected for the model. Values of kWh/kg needed by material are provided (Thiriez 2006). Also the energy consumption in kWh/kg can be determined by introducing the dryer's power and the kilograms to be dried. A typical drying time for the material is suggested by the program's database.
- Refrigeration: cooling of the mould is simulated as the specific heat of the part's material multiplied by the difference between the injection and ejection temperature, and divided by a coefficient of performance. The oil hydraulic's cooling is of great importance as well, due to the oil's temperature has to be maintained stable to assure a good performance. The kWh/kg required is modelled with a lineal correlation obtained from specifications of a chiller's manufacturer.
- Drivers: the energy requirements for mould clamping (opening and closure) and the extruder are incorporated to the model.

In addition to the electricity consumption, the machinery and the mould, needed to manufacture the plastic part, have to be included as well in the model.

Therefore the environmental impacts of metals like steel, aluminium or copper, which are part of the mould, are also assessed. They contribute to the final results proportionally, as a function of the quantity of parts produced with each one (Figure 5 and Figure 6). Its end of life scenario is also included, providing suggestions of percentage for recycling and landfilling.

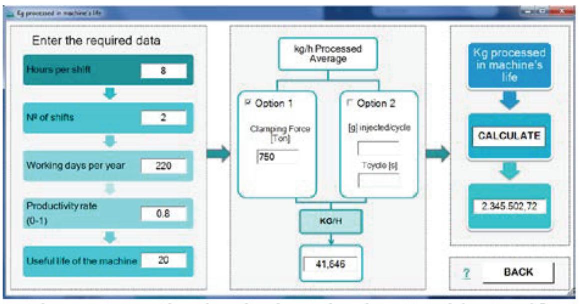

Figure 5: Production in the Injection Machine's Life

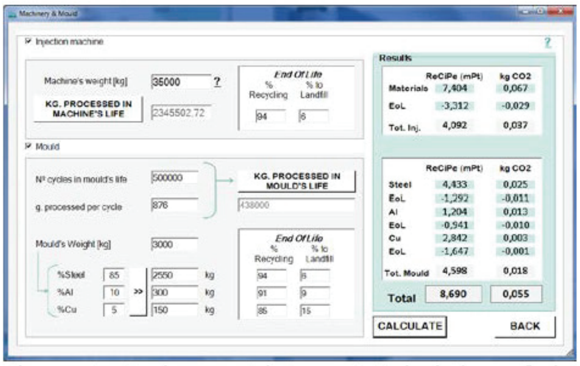

Figure 6: Environmental Impact Calculation of the Mould and the Injection Machine

The maintenance of the machine is also considered in the LCA model. The capacity of the oil tank has to be introduced along with the work hours between changes of the hydraulic oil in order to evaluate the environmental impact of the machine's maintenance. The environmental burden of the tank's oil has to be divided between all the kilograms injected during the time that has been used.

2.2.4. Packaging

Packaging materials like corrugated cardboard, expanded polystyrene, or plastic film, made for example of polyethylene, can be considered in this section. These three materials constitute a box in which one or several parts can be packaged. Also pallets can be introduced as a part of the packaging, dividing its environmental impact between the number of parts per pallet. As some of these packaging materials might be reused, a number of uses can also be assigned for pallets, wedges and cardboard to properly assess its environmental impact.
Giving the main dimensions of the part, an estimation of the packaging material needed can be done in a help's screen, taking into account the volume of the part.

2.2.5. Distribution to Client

Similarly to the raw material distribution, the transportation of the manufactured plastic part is taken into account in our model. Two different routes can be configured in order to give flexibility to the introduction of data.
Different scenarios can be simulated, for example if the plastic part is manufactured in a different factory than the assembly's factory. In both routes the user has to indicate the weight to be considered, net part's weight with or without the packaging weight.

2.2.6. End- of- Life

In this last phase, an end of life scenario is assigned for both the part and its sprue and the packaging materials, considering percentages of recycling, incineration or landfilling.
The percentage values suggested are from the technical report IEC TR62635 (IEC 2012), but they can be changed by the user if it is convenient to do so.
The sprue from the injection moulding process can be treated as the final part, or regrinded if it is reused in the same factory to inject another plastic part. If this alternative is selected, the environmental impact of this material will be subtracted from the total results. An electricity consumption value for the regrind process will be considered instead.
The end-of-life scenario for the packaging materials is also included in the LCA model, using values from Eurostat (Eurostat 2015).

3. CASE STUDY

In order to provide a clearer explanation of how the program works and give some quantitative results, an application example is going to be shown.

3.1. Part's Data

The plastic part that is going to be studied is a housing of an induction hob as the one analyzed by (Elduque et al. 2014a). Its function is to fix the electronic boards of the induction hob as well as closing the assembly. This plastic part is made of polyamide reinforced with glass fibre (PA66 GF30). It has a weight of 876 grams and its main dimensions are 460x415x40 mm (Figure 7).

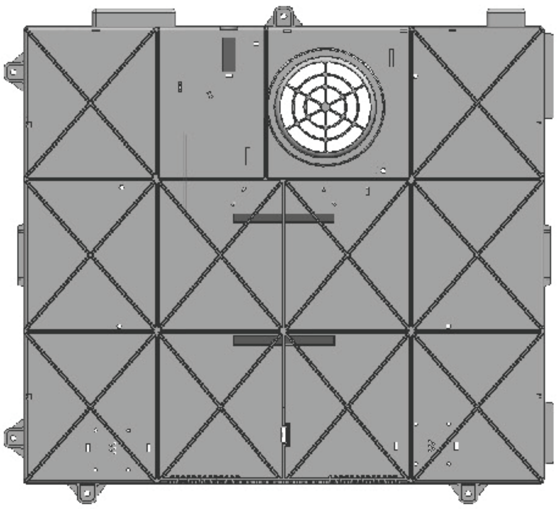
Figure 7: 3D Model of the Case Study Part

Its mould has only one cavity, and it has not got cold runners (Figure 8). This plastic part is injected in an injection moulding machine of 750 tons of clamping force.

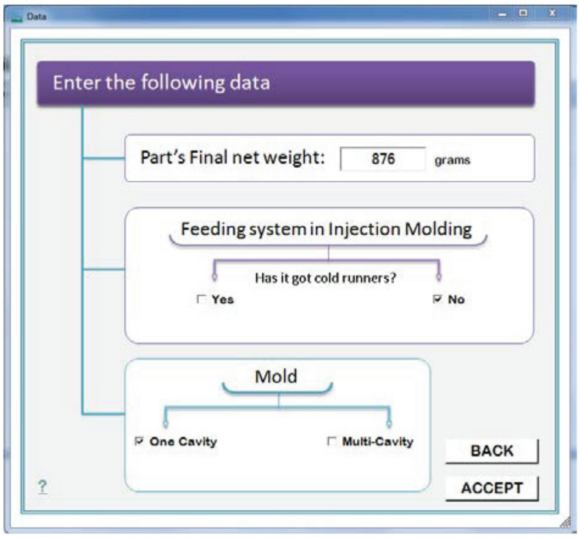

Figure 8: Data Required at the Start of the Modelling Case Study

3.2. Raw Material

Figure 9 shows the software's screen where the raw material is selected. For this case the "Nylon 6-6, glass-filled (RER) production" EcoInvent dataset was selected as the 100% of raw material. This thermoplastic has a high environmental impact in both studied categories. (522,6 mPt/part and 6,17 kg of CO_2 eq./part).

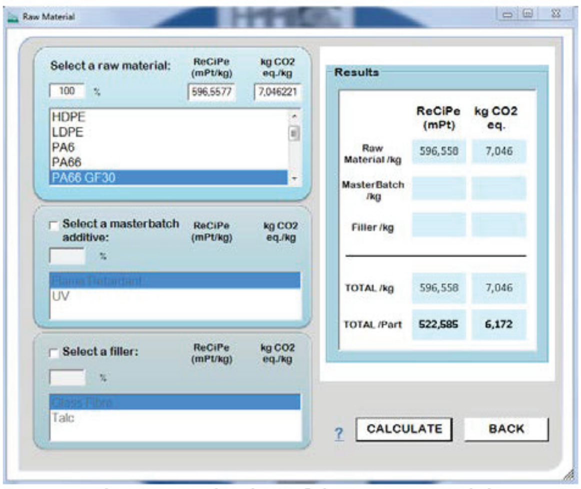

Figure 9: Selection of the Raw Material

3.3. Raw Material Distribution

A distance of three hundred kilometres is introduced to distribute the raw material to the factory by a >32 ton EURO 5 truck where the part is going to be manufactured. (Figure 10).

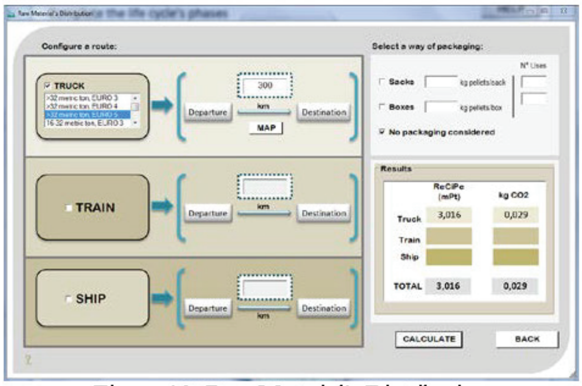

Figure 10: Raw Material's Distribution

3.4. Injection Moulding Process

To simulate the environmental impact of this phase, three subsections have to be completed. The most important one, as the results will show, is the electricity consumption. Figure 11 indicates the introduced data for the plastification phase, where the injection temperature is 300 ºC.

Also the consumption of the hot runner is estimated considering an equipment of 5.35 kW and a usage factor of 50%.

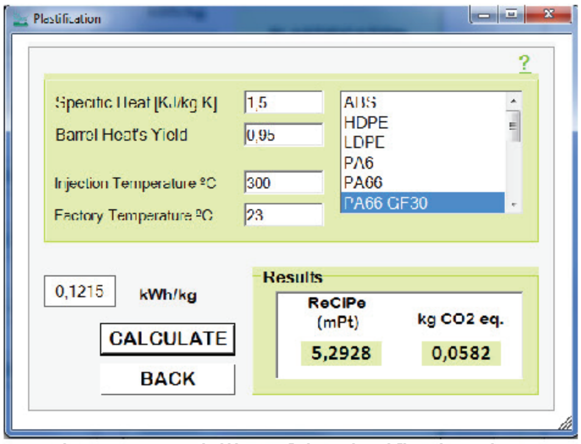

Figure 11: Modelling of the Plastification Phase

Using the program's help, a 2.2 kW power for the conveying system is selected, which for this case is an optimum working point taking into account the kg/h required by the manufacturing process (Figure 12).

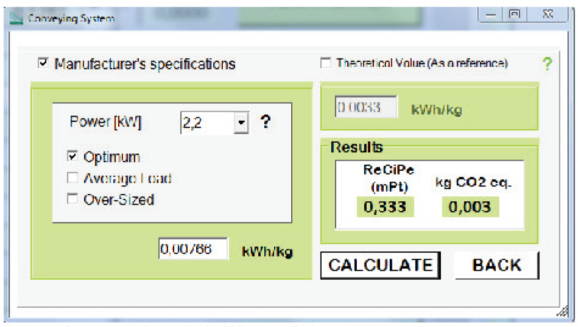

Figure 12: Modelling of the Conveying System

The raw material of this part (PA66) requires a drying process. A reference value of electricity consumption of 0.07 kWh/kg extracted from the literature is selected. The oil's cooling is considered in the refrigeration block considering the size of the injection machine.
Given that this component is manufactured in Spain, a Spanish electric mix is selected for this model. In Figure 13, the main screen for the electricity consumption collects the results of this section.

Figure 13: Modelling of the Electricity Consumption

An electricity consumption of 0,786 kWh/kg is obtained which is considered as an acceptable estimation, as this value is only a five percent higher than the one registered by the power measurement equipment (Elduque et al. 2014a).
It is worth noting that the plastification phase and the drivers of the injection moulding machine represents almost the 70% of the electricity consumption.
The second subsection to evaluate this manufacturing process is the Machinery & Mould. The injection moulding machine weights 35000 kilograms. As previously showed in Figure 5, a calculation of the kilograms produced during the useful life of the machine is used to evaluate its impact.
In addition the environmental impact of the 3000 kg-mould is divided between the total of kilograms processed in the mould's life, considering 500000 cycles (Figure 6). An end of life scenario is assigned for the steel, copper, and aluminium belonging to the injection machine and the mould. Also the hydraulic oil consumption is calculated (Figure 14).

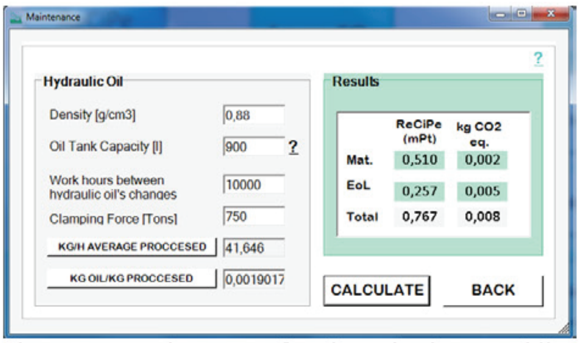

Figure 14: Maintenance for the Injection Moulding Process

The final results of the injection moulding process phase, are obtained by processed kilogram, therefore, in the total results this value will be multiplied by the part's gross weight (0.876 kg).
As it can be seen in Figure 15, the electricity consumption is the most influential factor in the environmental impact of the injection moulding process (nearly 80% of the impact simulation results for the ReCiPe methodology and almost 86% for the carbon footprint).

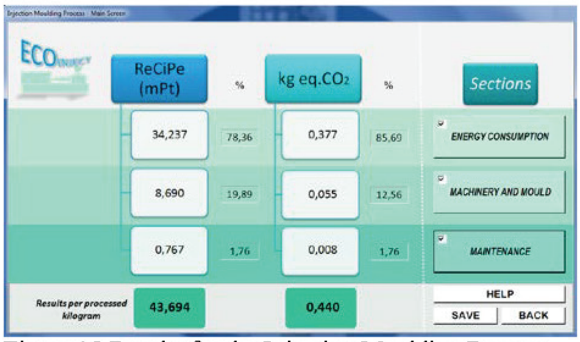

Figure 15:Results for the Injection Moulding Process

3.5. Packaging

The packaging required to distribute the manufactured part to the assembly plant is estimated as the next figure shows (Figure 16).

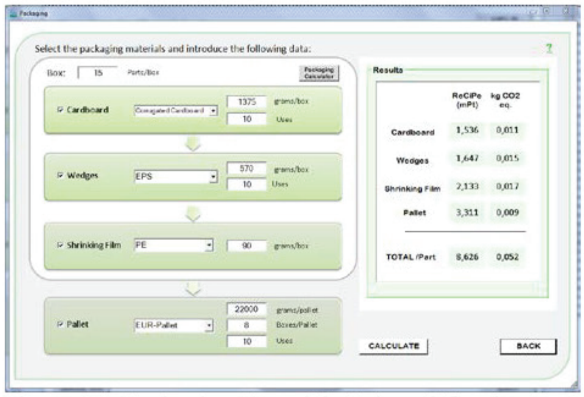

Figure 16: Packaging Materials Selected for the Case Study

3.6. Distribution

For this case study, two different routes are configured. The first one of 35 kilometres covers the distance between the injection factory and assembly's factory where this part will be assembled to the induction hob. The weight of the packaging materials is added to the part's weight for this calculation.
In addition, it is going to be considered the final distribution of this part to client, in order to observe the influence in the distribution's phase of the weight of this part. To achieve this, a total of 1800 kilometres by truck are considered (Pina et al. 2015).
For both routes a >32 ton EURO 5 truck is considered, using EcoInvent's dataset (Figure 17).

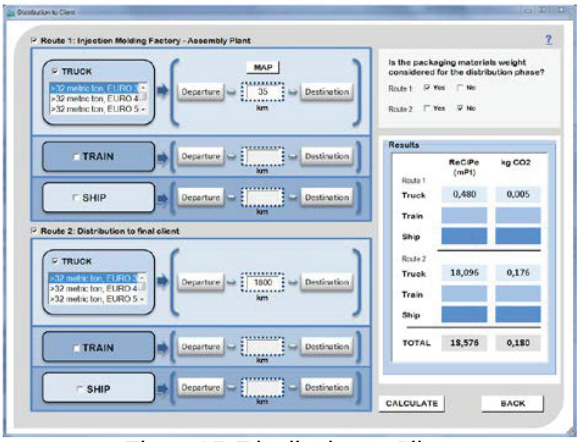

Figure 17: Distribution to Client

3.7. End of Life

As the material of this part is a reinforced thermoplastic, it is considered as not suitable for direct recycling and it is all sent to landfill, increasing the environmental impact of the material in 8,4 mPt/part, and 0,08 kg CO_2 eq./part. The end of life scenario for the packaging materials is included as well, as is indicated in Figure 18.

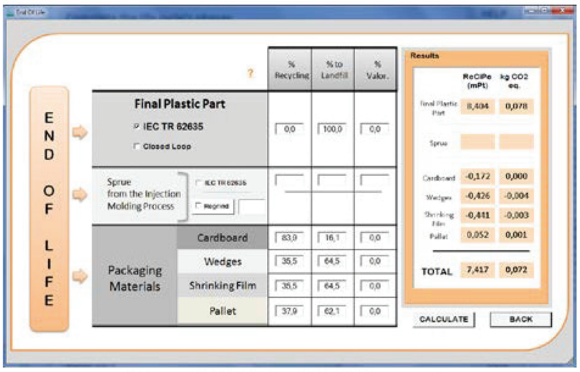

Figure 18: End-of-Life Scenarios

3.8. Results

Figure 19 summarizes the final results of this case study. The environmental impact of the polyamide is quite high in comparison with other thermoplastics. This causes that more than the 85% of the environmental impact for both categories is due to the raw material production. Nevertheless the manufacturing process contributes with more than 6% to the total results.

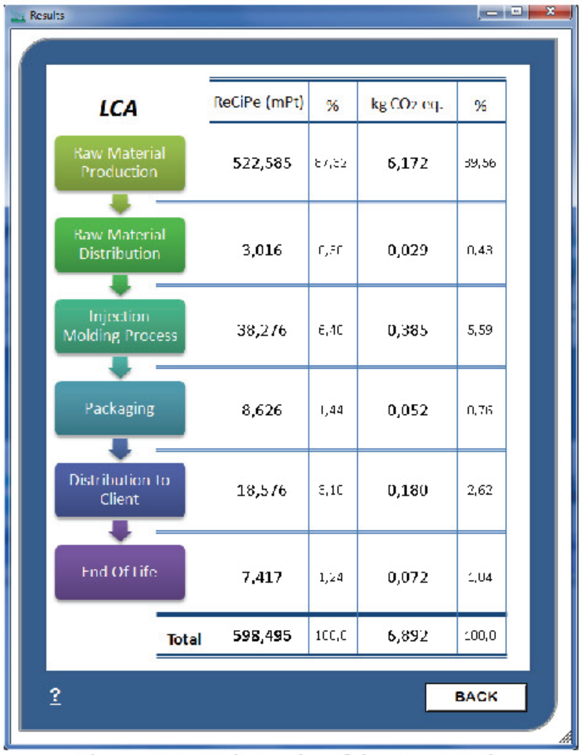

Figure 19: Total Results of the Case Study

4. CONCLUSIONS

The software shown in this paper simulates the environmental impact of an injected moulded plastic part by means of a LCA model. The results provided by this program allows designers to evaluate in detail the environmental impact of a specific plastic part and thereby simulate different alternatives, as the model is sensitive to many different parameters such as the raw material of the studied part, routes and means of transport used for distribution, the characteristics of the mould or the injection moulding machine that define the manufacturing process, or several end of life scenarios to complete the life cycle analysis simulation.

Results from the case study and other studied parts by the authors have shown that usually the most important phase, due to its higher environmental impact, is the production of the raw material but also the second one which has a remarkable importance is the manufacturing process, depending on many factors on which designers or engineers have influence.

Having this simulation tool implemented, our future work would be to relate these simulations of the harm caused to the environment, with the economic cost of the part's manufacturing. The modelling and simulation performed by this software would allow companies to evaluate in a two dimensional way the sustainability of their products. In addition, several alternatives could be compared, letting the engineer choose the most favourable case, achieving impact`s reductions from an economic and environmental standpoint.

REFERENCES

Aisa, J., Javierre, C., De la Serna, J., 2006. An example of simulation tools use for large injection moulds design: The CONTENUR™ 2400 l solid waste container. Journal of Materials Processing Technology, 175(1-3), pp. 15-19.

Borchardt M., Wendt M.H., Pereira G.M., Sellitto M.A., 2011. Redesign of a component based on ecodesign practices: environmental impact and cost reduction achievements. Journal of Cleaner Production, 19, pp. 49-57.

Cellura, M., Longo, S., Mistretta, M., 2012. Life Cycle Assessment (LCA) of protected crops: an Italian case study. Journal of Cleaner Production, 28, pp. 56-62.

Duflou, J.R., Kellens, K., Renaldi, R., Guo, Y., Dewulf, W. 2012. Critical comparison of methods to determine the energy input for discrete manufacturing processes. CIRP Annals - Manufacturing Technology, 61, pp. 63-66.

Elduque, A., Javierre, C., Elduque, D., Fernández, A., 2015. LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process. Sustainability, 7 (4), pp. 3792-3800.

Elduque D., Clavería I., Fernández, Á., Javierre, C., Pina, C., Santolaria, J. 2014a. Analysis of the Influence of Microcellular Injection Molding on the Environmental Impact of an Industrial Component. Advances in Mechanical Engineering, 6, pp 7.

Elduque, D., Javierre, C., Pina, C., Martínez, E., Jiménez, E. 2014b. Lice cycle assessment of a domestic induction hob: Electronic boards. Journal of Cleaner Production, 76, pp. 74-84.

Eurostat, 2015, Recycling rates for packaging waste, Available from: http://ec.europa.eu/eurostat/data/database [April 2015]

European Parliament, 2009. Directive 2009/125/EC of the European Parliament and of the Council of 21 October 2009 Establishing a Framework for the Setting of Ecodesign Requirements for Energy-Related Products, EU Publications Office, Luxembourg: Official Journal of the European Union.

Fernández, A., Javierre, C., González, J., Elduque D., 2013. Development of thermoplastic material food packaging considering technical, economic and environmental criteria. Journal of Biobased Materials and Bioenergy, 7(2), pp. 176-183.

Gerber A.G., Dubay, R., Healy, A., 2006. CFD-based predictive control of melt temperature in plastic injection molding. Applied Mathematical Modelling, 30, pp. 884-903.

Gutowski T., Dahmus J., Thiriez A., 2006. Electrical Energy Requirements for Manufacturing Processes. 13th CIRP International Conference of Life Cycle Engineering, May 31st – June 2nd, Lueven.

Huang Y., Yang G., 2012. The Applied Research of Green Production Technologies Based on the Production in Plastic Molding Factories. Energy Procedia, 14, pp.247-254.

IEC, IEC/TR 62635 Guidelines for end-of-life information provided by manufacturers and recyclers and for recyclability rate calculation of electrical and electronic equipment. Geneva, International Electrotechnical Commission.

Jiménez, E., Ruiz, I., Blanco, J., Pérez, M., 2009. Design and simulation of production of injection pieces in automobile industry. International Journal of Simulation Systems, Science and Technology, 10(3), pp. 23-30.

Jiménez, E., Martínez, E., Blanco, J., Pérez, M., Graciano, C., 2014. Methodological approach towards sustainability by integration of environmental impact in production system models through life cycle analysis: Application to the Rioja wine sector. SIMULATION, 90(2), pp. 143-161.

Lucchetta, G., Bariani, P.F., 2010. Sustainable design of injection moulded parts by material intensity reduction. CIRP Annals - Manufacturing Technology, 59, pp. 33-36.

Madan J., Mani, M., Lee, J.H., Lyons K.W., 2014. Energy performance evaluation and improvement of unit-manufacturing processes: injection molding case study. Journal of Cleaner Production, pp. 1-14.

Martinez, E., Sanz, F., Pellegrini, S., Jiménez, E., Blanco, J., 2009. Life cycle assessment of a multi-megawatt wind turbine. *Renewable Energy,* 34(3), pp. 667-673.

Martínez, E., Blanco J., Jiménez, E., Saenz-Díez J.C., Sanz F., 2015. Comparative evaluation of life cycle impact assessment software tools through a wind turbine case study. Renewable Energy, 74, pp- 237-246.

Müller E., Schillig R., Stock T., Schmeiler M., 2014. Improvement of injection moulding processes by using dual energy signatures. Procedia CIRP 17, pp.704-709.

Packianather, M., Chan, F., Griffiths, S., Dimov, S., Pham, D.T., 2013. Optimisation of micro injection moulding process through design of experiments. Procedia CIRP 12, pp. 300-305.

Park, H.S., Dang, X.P., Roderburg, A., Nau, B., 2013. Development of plastic front side panels for green cars. CIRP Journal of Manufacturing Science and Technology, 6, pp. 44-52.

Pina C., Elduque D., Javierre C., Martínez E., Jiménez E., 2015. Influence of mechanical design on the evolution of the environmental impact of an induction hob. International Journal of Life Cycle Assessment, 20(7), pp. 937-946.

Ribeiro, I., Peças, P., Henriques, E., 2013a. A life cycle framework to support materials selection for Ecodesign: A case study on biodegradable polymers. Materials & Design, 51, pp. 300-308.

Ribeiro, I., Peças, P., Henriques, E., 2013b. Incorporating tool design into a comprehensive life cycle cost framework using the case of injection molding. Journal of Cleaner Production, 53, pp. 297-309.

Simon, B. Amor, M.B., Földényi, R., 2015. Life cycle impact assessment of beverage packaging systems: focus on the collection of post-consumer bottles. Journal of Cleaner Production, pp. 1-11.

Spiering T., Kohlitz S., Sundmaeker H., Herrmann C., 2015. Energy efficiency benchmarking for injection moulding processes. Robotics and Computer-Integrated Manufacturing, 36, pp. 45-59.

Thiriez, A., 2006, An Environmental Analysis of Injection Molding, Massachusetts Institute of Technology.

Tsiropoulos, I., Faaij, A.P.C., Lundquist, L., Schenker, U., Briois, J.F., Patel, M.K., 2015. Life cycle impact assessment of bio-based plastics from sugarcane ethanol. Journal of Cleaner Production, 90, pp. 114-127.

Wäger, P.A., Hischier, R., 2015. Life cycle assessment of post-consumer plastics production from waste electrical and electronic equipment (WEEE) treatment residues in a Central European plastics recycling plant. Science of the Total Environment, 529, pp. 158-167.

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Influence of Material and Injection Molding Machine's Selection on the Electricity Consumption and Environmental Impact of the Injection Molding Process: An Experimental Approach

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Reducing energy consumption is an important issue for green manufacturing. In this paper, the specific energy consumption (SEC) of the injection molding process is analyzed. Results showed significant variations depending on the injected thermoplastic material and the type of injection molding machine (IMM) suggesting that IMM selection has a high relevance for the efficiency, cost and environmental impact of the process. The manufacturing of 36 plastic parts has been characterized by measuring the electricity consumption and obtaining the environmental impact, being this consumption its most important factor. A descending tendency for both is observed when high throughputs are obtained because the size of the IMM is more optimized. Conversely, the savings obtained by the all-electric IMMs are significant. This research could help engineers to properly select an IMM by taking into account the part weight, material and environmental criteria. Also, this study will be useful for life cycle assessment (LCA) practitioners. Real consumption data is presented, providing details about the materials, and relationships with the IMM that was used. The high variability suggests that if the injection molding process is relevant in a LCA study, its consumption must be analyzed in depth, preferably by measuring real consumptions in the factory.

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NOMENCLATURE

ΔT = Difference between room and injection temperature
η = Percentage of utilization of the IMM's capacity
E_{part} = Energy for the production of a plastic part (kWh)
E_{period} = Average consumed energy in sampling period (kWh)
E_{plast} = Required energy to heat the barrel during plasticizing phase (kWh/kg)
n = Number of cavities of the mold
ρ = Raw material density (g/cm^3)
SEC = Specific energy consumption
s_h = Specific heat of thermoplastic (kJ/kg K)
t_c = Cycle time (h)
$\tau_{sampling}$ = Sampling period (h)
V_{max} = Maximum injection volume of the IMM (cm^3)
w = Weight injected per cycle (kg)
y = Throughput (injected kg/h)

1. Introduction

As climate change and other environmental concerns become more relevant, industries have to deal with the growing pressure to decrease their carbon footprint and their environmental impact. New and more exigent regulations along with an increase in the cost of energy are likely to increase that pressure even more for manufacturing companies.[1]

Methodologies, tools, and databases have been developed over the last decades in the field of industrial ecology in order to assess, in a systematic and scientific way, the environmental footprint of products, processes and services, with the objective of identifying hot spots where actions would be more beneficial. Life Cycle Assessment (LCA) is one of the most developed methodologies that has been applied to calculate the environmental footprint of a wide range of products, processes and services. Wind turbines,[2] insulation panels,[3] small crafts,[4] electronic boards,[5] photovoltaic systems,[6] etc. are a few examples of the broad range of applications that can be assessed by this methodology by considering all of their life phases and allowing them to evaluate different design alternatives.

Manufacturing management systems conceived that cutting costs, such as implementing lean production, could also reduce the environmental impacts of industrial companies. For instance, the 5S technique (Separating, Setting in order, Shining, Standardizing and Sustaining) improves waste management and cellular manufacturing layouts to increase energy-efficiency.[7]

Several authors have researched the idea of including energy-efficiency criteria in the scheduling of production systems by means of energy consumption estimations on a machine level.[8] In addition to the improvement of the process's efficiency, the cost of production could also be optimized by taking into account the time-of-use variability of the electricity prices.[9]

There are numerous studies that have been published regarding energy consumption, specifically in the machining industry. These studies show several ways to improve the scheduling and energy efficiency to obtain more sustainable production. He et al.[10] take into account the machine tool's selection and the sequence of operations to reduce the energy consumption and achieve a more sustainable process. Mativenga and Rajemi,[11] analyze the optimum cutting parameters in order to reduce the energy and carbon footprint of the machining of products. Lee et al.[12] study how to reduce the energy consumption of a machine tool at the component level, modeling the behavior of the system, providing a profile of the use of energy and verifying the model experimentally. Behrendt et al.[13] proposed an energy consumption monitoring procedure to apply to machine tools by defining three different modes of operation: the standby power, the component power (main components: drives, spindles, pumps, etc.) and the machining power. Avram and Xirouchakis[14] studied the electricity consumption of a machine tool system by developing a methodology to estimate it and comparing their results to experimental data.

Kara and Li[15] proposed an empirical model to estimate the electricity consumption of the material removal processes, such as turning and milling. They selected the specific energy consumption (SEC, kWh/kg) as the reference to make comparisons between the processes.

One industry that could benefit from energy efficiency actions is the plastics transformation industry, which is currently of great importance in the global economy.[16]

From commodities plastics, such as polyethylene or polypropylene, to more technical or engineering thermoplastics, such as filled polyamides or polycarbonates, these raw materials are used in many products to fulfill various applications with the injection molding process being the most common way of manufacturing them. By measuring the energy demand of these production processes, the electricity consumption can be assessed and actions to improve the process' efficiency can be studied. Deng et al. [17] applied these ideas to the polymer extrusion process by using a power meter to record the energy demand of the process.

Similarly, Spiering et al.[18] performed an energy efficiency benchmark of the injection molding process highlighting the fact that, unlike the environmental impact assessment of the use phase of a product, which is usually studied in depth, the manufacturing phase does not usually have detailed Life Cycle Inventory data and the potential to recognize areas of improvement is very low. The high importance that the electricity consumption has on the environmental impact of the plastic injection molding process was shown in previous research.[19] The environmental impact of this process was also analyzed by applying a calculation methodology to several HDPE plastic parts for which the electricity consumptions were measured during the production conditions. A high variability in the energy process demand depending on the injection molding machine (IMM) and the characteristics of the part and process was observed in this study.[20]

In general, there is still a margin for improvements in the manufacturing industry, as Uluer et al.[21] noted in a case study performed in a home appliances factory. Some actions that enterprises should carry out are monitoring energy consumption and analyzing possible relationships between the consumptions and the manufactured products.

These actions would allow for identifying ways to reduce the energy consumption, along with the environmental and economic impact of the industrial activity.

Following this idea, in this paper an experimental study of the electrical consumption of the injection molding process at the machine level is carried out. The results of the electricity consumption from a total of 36 case studies during the production of different plastic parts made from several kinds of thermoplastics and injected in different IMMs are collected.

These measurements can also be used to assess the environmental impact of the manufacturing of injected plastic parts. Using a methodology previously published by the authors,[20] the environmental impact for the injection molding process will also be calculated for the studied parts.

In the following section, a state of art review focusing on the injection molding process will be carried out. The "Materials and Methods" section will cover the details of the required equipment used during this research such as the measurement equipment and procedure, the analyzed IMMs and the plastic parts. Additionally, the methodology used for the calculation of the environmental impact results will be discussed. Then, the results (of electricity consumption and environmental impact) and discussion will be addressed in section 4.

2. State of the Art Review

Although injection molding is a widely studied manufacturing process in scientific literature, its main research areas have been polymer properties or production improvements; however, the variability in the energy consumption has not been analyzed in depth. Injection molding allows for the manufacture of plastic parts with complex geometries. Several phases make up the cycle of this process: the plasticizing phase when the raw material is melted, the filling of the mold, the holding of the injection pressure to assure complete filling of the part, and the cooling and ejection of the part. Some of these phases occur simultaneously. Several studies where this process is analyzed show an estimation of the energy breakdown for the injection molding process. The most intensive phases of it are the barrel heating included in the plasticizing phase, and specifically all of those phases that involve movements of the machinery, such as mold clamping or the rotation of the screw.[22]

Many authors have developed optimization methods for the process' parameters for the CAE simulation tools. For example, the method presented by Kitayama and Natsume,[23] where the optimal parameters were obtained by minimizing both the volume shrinkage and the clamping force, and taking as a constraint the absence of short shots. They also noted that a lower clamping force would lead to higher productivity and lower costs per produced part, and that the use of a smaller IMM also influences the electricity consumption of the whole process. New ways of cooling systems are also evaluated in the literature in order to obtain a more efficient process by reducing the cooling time, which represents up to 80% of the molding cycle time in most of the cases.[24] To improve the quality of the product, a higher temperature of the mold is required during the filling phase but to decrease the molding cycle, this temperature has to drop significantly. There are different developing techniques called rapid mold heating and cooling methods, that try to achieve this by using electric, steam or induction heating and water cooling.[25,26]

Some studies have also focused on the energy efficiency of the process by analyzing the electricity consumption of the process. In the research performed by Spiering et al.,[18] an energy efficiency benchmarking of the injection molding process in the automotive industry was carried out. With this study, the authors tried to gain knowledge that would allow for identifying the best practices, improvements for product designs, or predictions of the energy consumption of production plants. A structure to create an energy monitoring system (EMS) is proposed by these researchers. From measurements, they obtained a correlation of the SEC (kWh/kg) vs. material throughput (kg/h). The coefficient of determination (R^2) for this correlation was 0.7 because the process' efficiency depends on the combination of the machine, mold, part, material, etc. Nevertheless, the data presented in this paper is very general and does not indicate details about the characteristics of each measured part in which IMM was injected or the absolute values of the SEC.

Only detailed data for one part is provided. An SEC value of 1.55 kWh/kg in series production is obtained for a 3500 grams part, made out of PP with a 20% glass fiber content. This part was injected in an IMM with approximately 2000 tons of clamping force. However, data such as the cycle time of the Spiering's process, driver's technology or machine's capacity is not given.

Other authors such as Lu et al.[27] have developed algorithms to find the optimal parameters considering energy savings and quality specifications, giving this quality requirement priority over energy consumption. As these authors indicated, the relationship between energy consumption and the process's characteristics is a complex nonlinear model.

Park and Nguyen[28] presented another study on the optimization of the injection molding process, which they applied to the manufacturing of a car fender. They enumerated two possible ways to obtain energy savings. The first one was the one that would require much less cost and was the optimization of the process parameters based on a mathematical and energy model. The other alternative to obtain energy savings was the improvement of the machinery or the investment in new and more efficient technologies. Depending on the type of technology that is used to drive their movements, IMMs are commonly classified into three groups: the more conventional hydraulic machines running with hydraulic pumps at a fixed speed, hybrid machines that are machines that have the injection unit electrified, or other configurations that combine hydraulic and electric systems, and all-electric units that, as their name indicates, lack a hydraulic system.

These all-electric machines could achieve energy savings from 30-70% compared to other machines since the conversion of energy is more direct.[29]

Lower electricity consumption is not the only advantage of all-electric machines. They also require less maintenance since there is no hydraulic oil to replace. This also saves time in the start-up process. The motion of the clamps is faster too, allowing shorter cycles. On the other hand, high injection rates cannot be achieved by these all-electric machines, so larger parts have to be injected in hydraulic or hybrid IMMs with higher clamping forces.

An IMM manufacturer performed an experimental study with three IMMs of the same clamping force (240 ton) but different drives: one hydraulic, a hybrid and an all-electric.[30] Their SEC was measured during the production of a small part that weighted 106 grams and had a cycle time of 20 seconds. The raw material was not indicated in the study. The results showed an SEC of 0.44 kWh/kg for the hybrid, which was 1.6 times higher than the all-electric's (0.27 kWh/kg). On the other hand, the less efficient system (hydraulic) obtained an SEC of 0.65 kWh/kg, which was 2.4 times higher than the all-electric machine and 1.5 times the SEC of the hybrid machine. When increasing the cycle times, the SEC for all of the machines increases as the throughput decreases.

It is clear that there is an increasing concern about how to reach greener manufacturing processes; nevertheless, considering the reviewed state of the art and the previous work of the authors, a potential for further research in the field of the energy consumption of the injection molding process is detected. Ways to optimize through simulation models are widely discussed but there is still a lack of experimental data available in the literature. Although some benchmarks are published, not very detailed values can be derived from these studies.

On the other hand, the environmental impact related to the process is also determined as an area to be studied more deeply because there is usually a lack of data that needs to be covered to complete the Life Cycle Inventory of the manufacturing phase of a product.[18]

Through the experimental measurements performed during this research, useful information is expected to be obtained both for production engineers and LCA practitioners providing real consumption data for the injection molding process. The influence of the raw material and the relationship of the IMM with the characteristics of the injected plastic parts will be analyzed in the results section.

3. Materials and Methods

In the following section, the equipment that was used to perform the experimental energy measurements is going to be presented along with the main characteristics of the IMMs that were measured and the thermoplastic materials of the manufactured parts. Additionally, the calculation methodology to obtain the environmental impact results is going to be explained.

3.1 Measurement Equipment and Procedure

The equipment to perform the experimental measurements shown in Fig. 1 is the same equipment that was described in a previous study by the authors.[16] It is composed of a portable energy monitoring device (Circutor C-80) that records all of the IMM consumption and the auxiliaries connected to it. To measure the consumed power, clamps were placed to meter the current intensities of the machines in the electric panel. Three different clamps were used for these measurements (Figs. 1(c)-(e)) and each of them was adequate for a range of intensities. Voltage wires were also used to measure the electricity consumption.

The maximum intensity must be checked before the measurements start in order to select the correct current clamp. A sampling period that covers several cycles must be selected. In addition, production must have been stable for two hours before the measurement to avoid the start-up periods. An average of three hours per test is defined to achieve enough data to ensure the validity of the measurement.

Afterwards, the energy consumption data collected by the portable device is analyzed. An average consumed energy value during the sampling period is obtained. If production was not stable during the measurement, the measurement procedure is repeated.

Fig. 1 Measurement equipment: (a) Energy monitoring device, (b) Voltage wires, (c)-(e) Clamps, (f), (g) Crocodile clamps (for voltage wires), (h) Security gloves

In addition to the recording power device, several bascules were used in order to measure the gross weight of the plastic parts. Additionally, a chronometer was used to record the cycle time. Measurements were performed in three different large factories in Madrid and Zaragoza (Spain), being the work environment the average of a factory plant with temperatures between 18-23°C.

The required consumption for the production of the plastic part will be determined as follows in Eq. (1):

$$E_{part} = \frac{t_c \times E_{period}}{\tau_{sampling} \times n} \tag{1}$$

The cycle time and the weight injected per cycle are needed to obtain the throughput Eq. (2).

$$y = \frac{w}{t_c} \tag{2}$$

With the obtained values from Eqs. (1) and (2), the SEC (kWh/kg) can be calculated as indicated in Eq. (3).

$$SEC = \frac{E_{part} \times n}{w} \tag{3}$$

3.2 Injection Molding Machines

A total of 12 different IMMs were measured during stable production, the operation parameters were optimized by production engineers in order to assure the quality of the manufactured parts.

The goal was to obtain data from as wide a range of IMMs as possible. In this paper, the 12 measured IMMs have a clamping force from 85 tons to 8000 tons. The main characteristics of the machines, such as their clamping force and maximum injection volume, are included in Table 1. The maximum injection volume value included in Table 1 is used to calculate the utilization percentage of the IMMs during the production of each plastic part Eq. (4). This percentage will be considered to analyze the results in section **4**.

$$\eta = \frac{w \times 1000}{\rho \times V_{\max}} \times 100 \tag{4}$$

Table 1 Measured Injection Molding Machines

IMM	Type of machine	Clamping force (Tons)	Maximum Injection Volume (cm^3)
A	Hybrid	8000	110000
B	Hybrid	5200	65339
C	Hybrid	3000	19300
D	Hybrid	2000	3721
E	Hybrid	1650	3721
F	Hybrid	1200	5400
G	Hybrid	1000	3721
H	Hybrid	750	4545
I	Hybrid	400	1391
J	Hybrid	200	523
K	Hybrid	125	217
L	All-electric	85	97

3.3. Plastic Parts

Table 2 summarizes the main characteristics of the 36 parts from which the manufacturing process was measured. It indicates the raw material, the machine where the part was injected, the weight injected per cycle, the measured cycle time and the number of mold cavities. Photographs of all of the measured parts are shown in Fig. 2.

3.4. Environmental Impact Assessment Methodology

To calculate the environmental impact of processing these plastics parts, an adaptation of the methodology described in our previous research is going to be applied.[26] In the previous article, an analysis on how the EcoInvent v3 Life Cycle Inventory database characterizes this process was conducted. To assess the environmental impact of the HDPE plastic parts, a customized dataset was prepared: removing elements not directly related with the injection molding process, considering data values of a more conventional thermoplastic (PP) instead of the EcoInvent's average obtained from values of PVCs, PPs and PETs processing factories, and replacing the average electricity consumption value with the SEC of each part. The European electric mix was selected in order to allow for a comparison to the original EcoInvent dataset.[26] The electricity consumption of the process was proven to be, in this

Fig. 2 Measured parts

Table 2 Measured parts

Part number	Description	Thermoplastic	IMM	w (g)	t_c (s)	n
1	Container (2400l)	HDPE	A	71800	216.00	1
2	Container (1000l)	HDPE	B	30300	147.00	1
3	Container lid (3200l)	HDPE	C	10500	175.00	1
4	Container lid (2200l)	HDPE	C	8700	194.00	1
5	Encasement #1	PP	C	7258	140.20	1
6	Car bumper	PP+EDPM+PE+10T	C	4695	118.00	1
7	Car front part #1	PP+EDPM+10T	C	3773	106.00	1
8	Car interior part #1	PP+EDPM+15T	C	1802	77.60	1
9	Car front part #2	PP+EDPM+20T	C	1589	91.00	1
10	Weatherproof luminaire diffuser (Alhama 2 × 58)	PC	D	646	22.00	1
11	Weatherproof luminaire housing (Aragón 2 × 36)	PC	E	745	33.70	1
12	Paper bin	HDPE	F	2778	139.00	1
13	Car interior part #2	PP	F	1560	70.00	2
14	Paper container part	HDPE	F	1253	81.00	1
15	Weatherproof luminaire diffuser (PE 2 × 36)	PC	G	495	24.40	1
16	Weatherproof luminaire diffuser (PE 2 × 36)	PMMA	G	489	29.05	1
17	Weatherproof luminaire diffuser (PE 1 × 36)	SAN	G	383	24.55	1
18	Encasement #2	PP	H	3407	100.00	1
19	Paper container small part	HDPE	H	836	40.00	1
20	Container part	HDPE	H	1336	162.00	1
21	Ring	HDPE	H	260	42.90	1
22	Container pusher	POM	I	310.75	37.60	2
23	Car bumper lid	PP	I	288	84.00	2
24	PA filled part #1	PA+50% LF	I	128.58	48.00	2
25	Container lock bar	PA	I	161.24	29.20	1
26	Shock absorber housing	HDPE	I	154.12	47.68	2
27	Ring 2 (350 mm)	HDPE	I	106.00	40.30	1
28	Container axis part	HDPE	I	100.50	44.40	8
29	Weatherproof luminaire lid	ABS	J	39.58	22.00	1
30	Weatherproof luminaire snap-fits (3 pieces)	PA	K	67.66	14.00	4
31	PA filled part #2	PA+30% GF	L	68.00	37.20	2
32	Container axis part	PP (100% recycled)	L	100.48	45.00	8
33	Container red ball	ABS	L	37.00	53.00	2
34	PA part	PA	L	16.08	11.80	2
35	Container snap-fit	PP	L	14.36	12.50	4
36	Container snap-fit	HDPE	L	15.00	15.00	4

previous study, the most important factor in the environmental impact results. It was also shown how the electricity consumption can differ greatly from the EcoInvent dataset's SEC value (1.47 kWh/kg).[31]

For this study, the Spanish electric mix is going to be used instead of the European because all of the plastic parts were manufactured in Spain. In addition, for the plastic parts that were injected in the all-electric machine, the environmental impact of the lubricating oil of the machine will not be taken into account. Therefore, the functional unit that will be assessed to calculate the environmental impact of the processing of 1 kg of injected plastic will contain the values derived from the EcoInvent methodology summarized in Table 3.

To calculate the environmental impact of this dataset, the software SimaPro 8 has been used.[32] The results are reported in mPt of the ReCiPe- Endpoint indicator. This methodology is recommended in the literature when only one value is required,[33] which will facilitate engineers to choose between different IMM options.

4. Results and Discussion

4.1 Energy Measurement Results and Discussion

In this section, the results of the experimental measurements are going to be presented and analyzed.

Different representations are going to be displayed in order to analyze and draw conclusions from the performed measurements. First, the relationship between the SEC and the kg/h injected per part or the utilization of the capacity of the machine will be discussed, analyzing and sorting the data by the IMM and by the material. Additionally, the results of the measurements where the same geometry was injected in different machines or with different raw materials will be analyzed.

The total required electricity to manufacture each plastic part was calculated, as explained in section 3.1. The results are shown in Table 4.

Table 4 shows that, generally, the heavier a plastic part is the more kWh are consumed to manufacture it. However, the real phenomenon is much more complex because several factors play an important role in energy consumption, such as the cycle time, IMM or material properties. An example of this can be seen with part #8, which has lower energy consumption and more weight than part #9. From Table 2, it can be observed that cycle time is higher for part #9, which justifies the higher energy consumption. From now on, in order to properly analyze the measurements, and establish comparisons between the case studies, the results will be presented based on the functional unit (1 kg of injected plastic part) using the SEC value. Fig. 3 shows the calculated SEC values for each analyzed part.

The average value for the measurements is 1.056 kWh/kg, which is 28.2% lower than EcoInvent's SEC value (1.47 kWh/kg). It can also be seen that the variability in the results is high. The standard deviation of this sample is 0.543 kWh/kg and its coefficient of variation (CoV= $\sigma/\overline{X}$) is 51.4%. The maximum SEC value is observed for part #9 injected in machine C (2.563 kWh/kg) and the minimum is for part #31 injected in machine L (0.375 kWh/kg). It is important to notice that the all-electric machine (L, #31- #36) registers the lowest average consumption per kilogram (0.529 kWh/kg).

Analyzing the distribution of the measurements, the majority of the SEC values (22 of 36) are approximately in the range between 0.4-1.2 kWh/kg. The analyzed samples do not exhibit a direct relationship between the size of the machine/part and the SEC, as can be observed

Table 3 Dataset for the environmental impact calculation

Description	EcoInvent v3 dataset	Value
Lubricants for hydraulic circuits	Lubricating oil {GLO}| market for | Alloc Def, U	1.67E-05 kg
Water	Water, cooling, unspecified natural origin	1.11E-02 m^3
Electricity	Electricity, medium voltage {ES}| market for | Alloc Def, U	Measured SEC (kWh/kg)
Plastic waste	Waste plastic, mixture {GLO}| market for | Alloc Def, U	0.005 kg
Infrastructure	Packaging box factory {GLO}| market for | Alloc Def, U	1.43E-09 p

Table 4 Total energy consumption for the manufacture of the plastic parts

Part number	Weight injected per cycle (g)	kWh/part	Part number	Weight injected per cycle (g)	kWh/part
#1	71800	30.949	#19	836	0.593
#2	30300	23.870	#20	1336	1.805
#3	10500	9.273	#21	260	0.598
#4	8700	9.287	#22	310.75	0.087
#5	7258	7.232	#23	288	0.184
#6	4695	5.698	#24	128.58	0.124
#7	3773	4.553	#25	161.24	0.192
#8	1802	2.912	#26	154.12	0.126
#9	1589	4.072	#27	106.00	0.189
#10	646	0.567	#28	100.50	0.023
#11	745	0.866	#29	39.58	0.048
#12	2778	1.442	#30	67.66	0.011
#13	1560	0.375	#31	68.00	0.013
#14	1253	1.128	#32	100.48	0.005
#15	495	0.539	#33	37.00	0.013
#16	489	0.493	#34	16.08	0.005
#17	383	0.359	#35	14.36	0.002
#18	3407	2.204	#36	15.00	0.002

with the heavier parts injected in the IMMs: "A, "B, and "C. This indicates that the electricity consumption is not directly related to the machine's size but to the relationship between the IMM and the injected part. On the other hand, only the all-electric machine (L), achieves consumptions lower than 0.4 kWh/kg in these case studies.

The IMM type is not the only influence on the SEC. Fig. 4 shows the SEC of all of the measurements against the throughput of every part by sorting the data by the machine's clamping force. This graph shows that for the same throughput value, not only can the SEC differ significantly, but the injection molding process also has a very wide throughput range with a maximum value for the measured parts up to 1200 kg/h and a minimum value of 2.5 kg/h.

A descending tendency for the consumption is observed in Fig. 4 as the throughput increases, as shown in the studies mentioned in the state

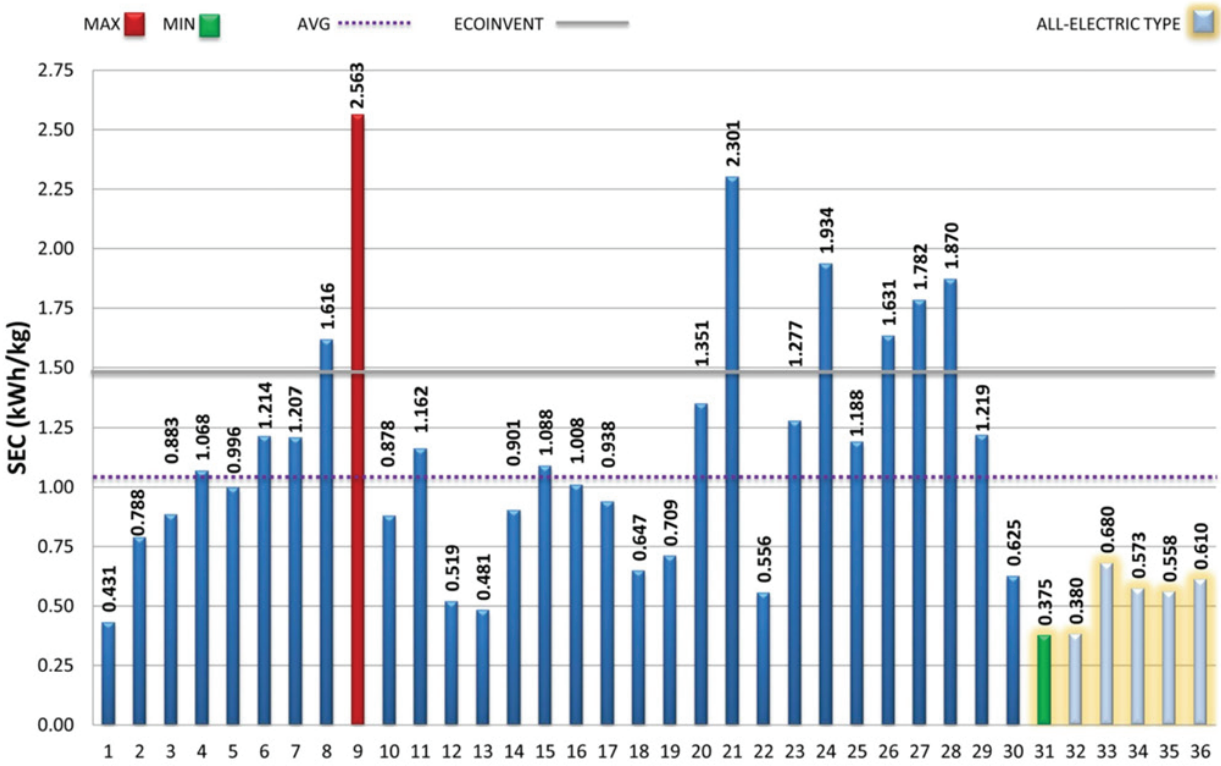

Fig. 3 SEC of all of the measurements

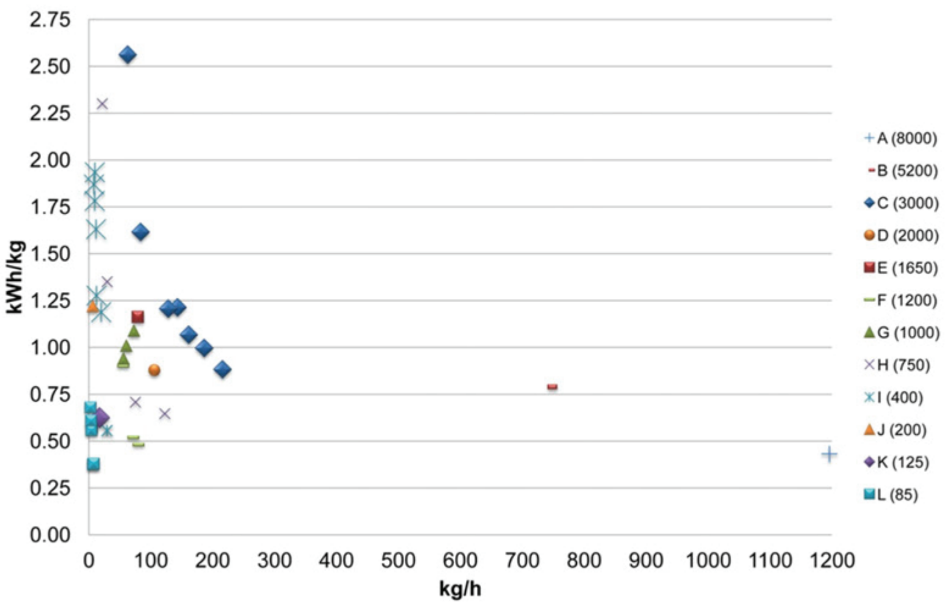

Fig. 4 SEC vs. throughput (sorting by IMM)

of the art review. Moreover, differences between the IMMs are also relevant. By isolating the results from the IMMs with at least four measurements (IMMs: C, H, I and L), Fig. 5 shows how potential functions for each IMM can be correlated with the experimental data with high R^2 values (> 0.875). The more clamping force the IMM has, the more displaced the curve is to the right zone of the graph. That is, in general, for the same throughput value, the SEC will be higher for the IMM that has a higher clamping force.

This tendency is characterized by the correlation value (R^2), which makes physical sense because the constant process' consumption necessary to keep the machine functioning during idle times, is divided by more kilograms per hour. Linear regression analysis (LRA) has been a useful method to identify the best practices and establish benchmarking baselines.[34]

To further analyze these tendencies, the relationship between the utilization percentage of the IMM and the SEC of the process is calculated by Eq. (4). It is expected that as the utilization of the IMM is near its full capacity, obtaining higher throughputs, its electricity consumption would be divided by the maximum possible plastic weight; therefore, the choice of machine size will be optimized for that part. Using Eq. (4), the relationship between the use of the IMMs capacity and the electricity consumption of the process can be analyzed (Fig. 6).

As with the throughput, a descending tendency of the electricity consumption is observed; however, unlike with the throughput, with this percentage, differences caused by the IMMs sizes are not shown because this is a dimensionless parameter. With this approach,

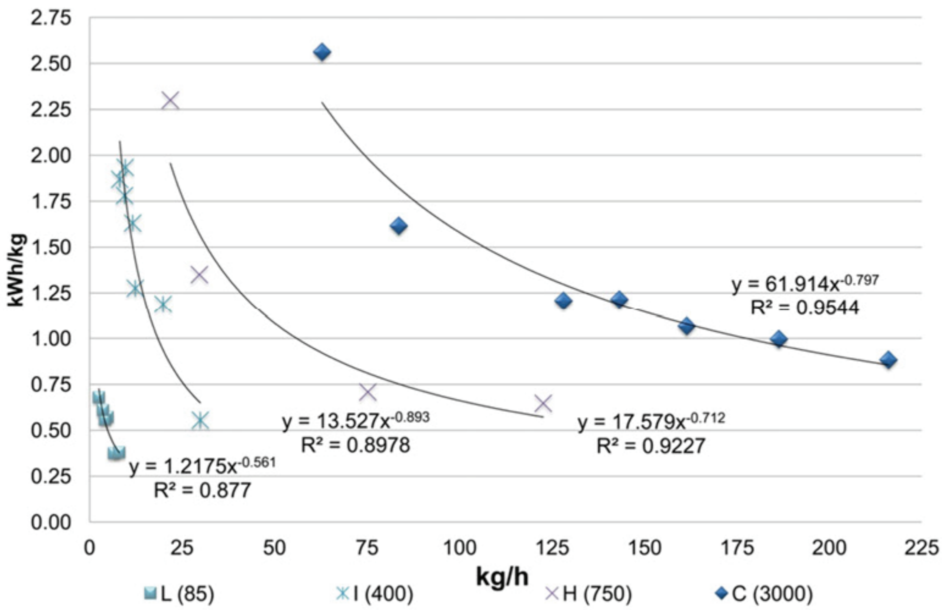

Fig. 5 Potential correlations: SEC vs. throughput (sorting by IMM)

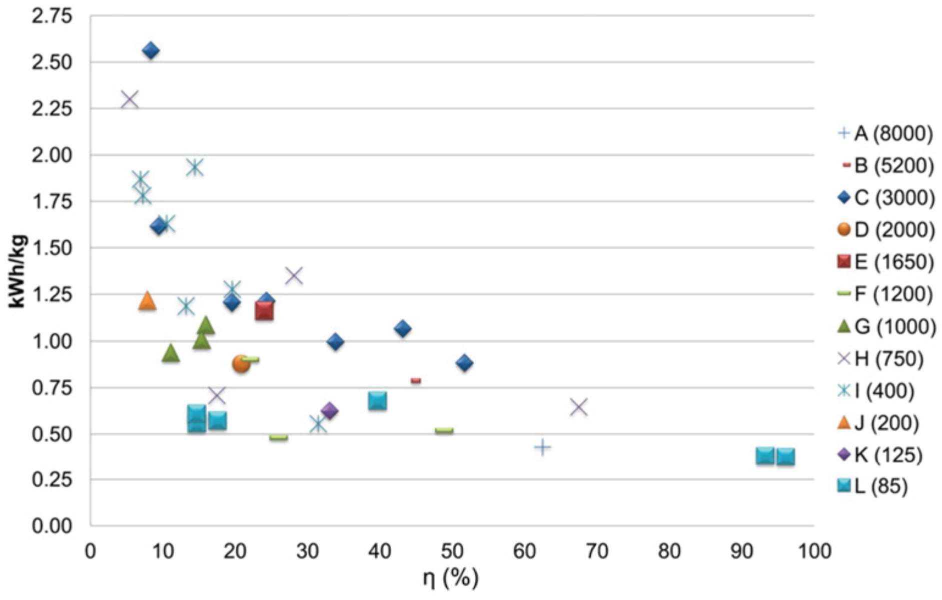

Fig. 6 SEC vs. η (sorting by IMM)

comparisons between the IMMs can be made by taking into account their used capacity. Generally, the higher the percentage of the machine's capacity that is used, the less kWh per kg is required for the injection molding process. However, smaller differences can be observed for the "L" machine (85 tons, all-electric), which maintains low SEC values regardless of the percentage of utilization of the IMM. The all-electrical configuration explains this result.

To analyze the influence of the material, the relationship between the percentage of utilization of the IMM and the SEC are shown in Fig. 7 for all of the materials. These results show that the studied PP filled parts registered the highest SEC values, as was reflected in the study by Spiering et al.,[18] but it also has to be taken into account that the machines used to manufacture them have low utilization percentages. The unfilled PPs parts, which have lower SEC values, even with low percentages of utilization, are all injected in the "L" machine (85 tons, all-electric).

Because Fig. 7 does not show any clearly defined tendencies, to continue identifying the influence of the raw material in the electricity consumption of the process, the results of the IMMs with four measurements or more (IMMs: C, H, I and L), shown in Fig. 5, have been sorted by material, namely, HDPE, PP, PP filled, POM, PA, PA filled and ABS (Fig. 8).

In Fig. 8, it can be observed that the majority of the measurements follow the descending tendency of SEC vs. throughput, as can be clearly seen for machines "C" and "H". For the "I" machine (400 tons) there are measurements that deviated slightly more from this mentioned tendency. For example, the one that corresponds to part #24, made out of filled PA with a very high percentage (50%) of long glass fiber, which has a slightly higher SEC than the tendency would indicate. This can be caused by the use of glass fiber fillers that generate an increase in the melt viscosity.[35] Moreover, the PA itself is an amorphous thermoplastic, which means that the macromolecular chains of the amorphous thermoplastics are entangled with no particular order and since the melt's viscosity depends on this structure, this raw material has a high viscosity that increases the SEC.[36]

There are also some interesting combinations to analyze in the measurements, which focuses on the part's characteristics. For example, parts #35 and #36, shown in Fig. 8, have the same geometry and they are injected in the same IMM ("L"). However, their raw material is different. In this case, the manufacturing process of the #36 HDPE part registers a higher SEC than the PP part (#35) (+9.3%). This result may be due to slight differences in the specific heat of these two thermoplastics, which causes the required energy for the plasticizing phase in the HDPE part to be higher. This stage is one of the most intensive phases of the process in terms of energy. The required energy to heat the barrel during the plasticizing phase could be estimated as indicated in Eq. (5).[37]

$$E_{plast} = \frac{s_h \times \Delta T}{3600} \tag{5}$$

Although the barrel has insulation, due to possible losses to the surroundings, a coefficient to include the possible yield of the system would have to be considered, but because the purpose of this analysis is to obtain a first estimation and in this case the losses are machine dependent, the value of this yield coefficient would be considered to be 1.

Another explanation for the obtained differences can be found in the requirements for the cooling phase since the recommended ejection temperature for the PP is 70°C whereas the temperature is 50°C in the HDPE part; therefore, the cooling time requirement for the PP part is lower and the total cycle time will be lower for the #35 PP part, as shown in Table 2.

Parts #28 and #32 also have the same geometry, but they are injected in different IMMs, the raw material is different (HDPE and PP, respectively) and the IMM is different. A high utilization of the capacity of the machine combined with the use of a more efficient technology (all-electric) allows for obtaining one of the lowest SEC

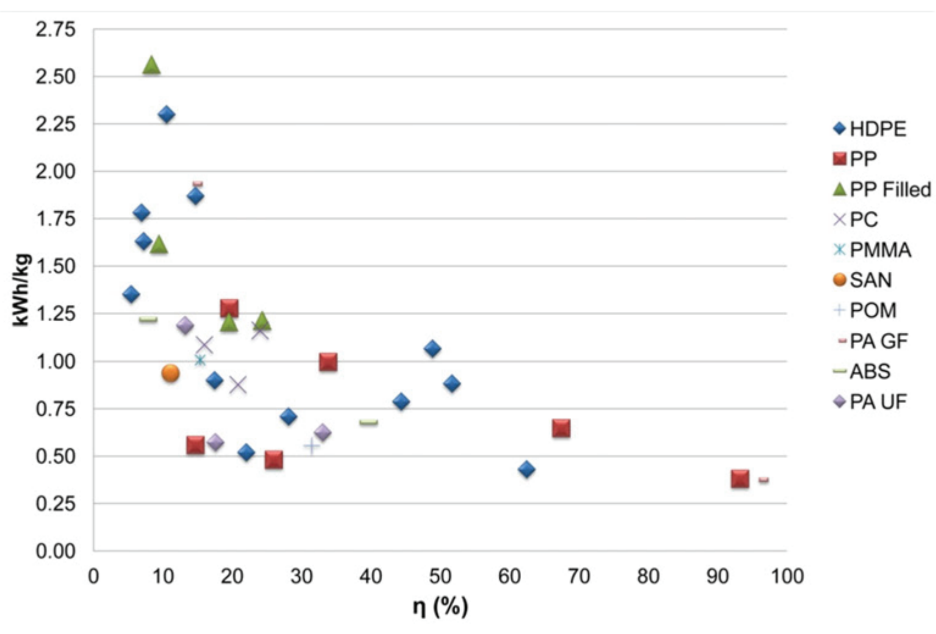

Fig. 7 SEC vs. η (sorting by raw material)

values for part #32 (0.38 kWh/kg). The low utilization of the "I" hybrid machine for part #28 manufacturing leads to a much less energy efficient process.

As previously discussed for part #24 in the explanation of Fig. 8, from samples #15 and #16, the role of the raw material's viscosity can also be analyzed. For these samples, the IMM and the part geometry

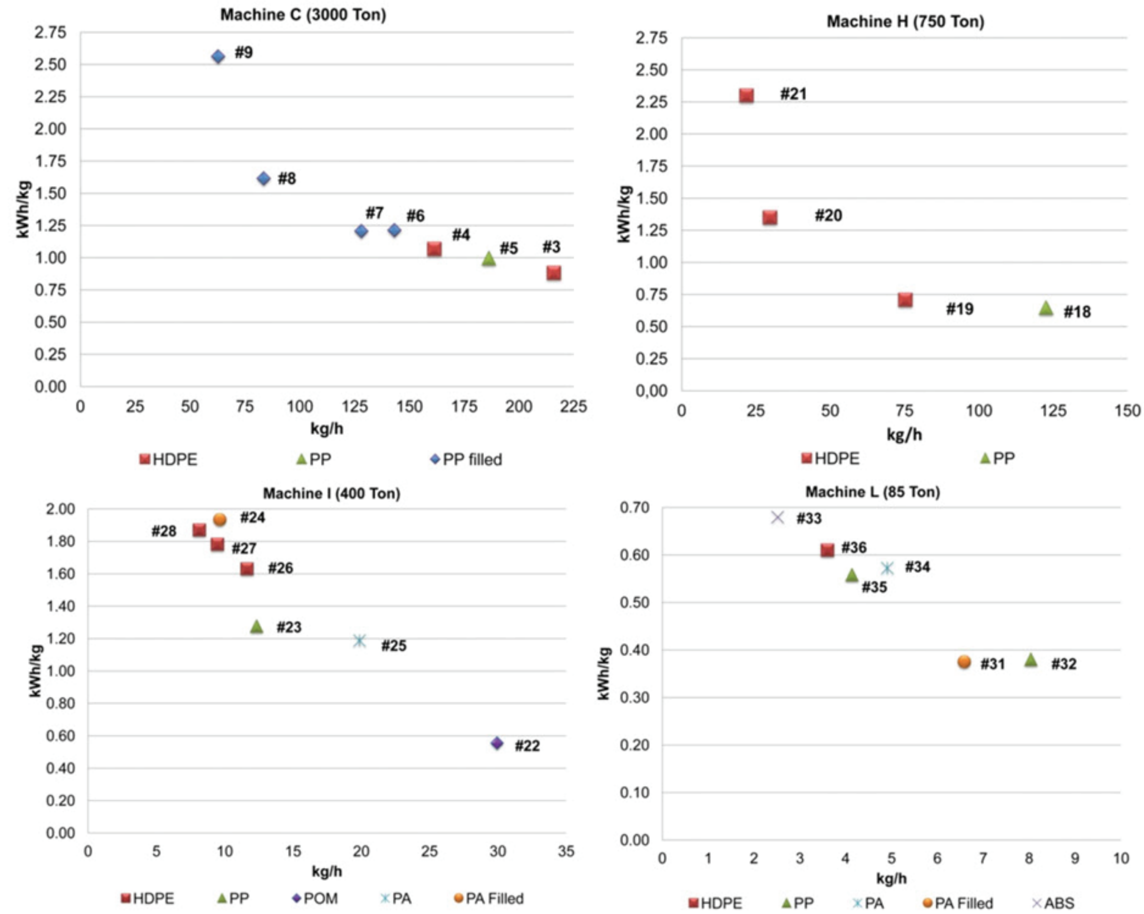

Fig. 8 SEC vs. kg/h (IMMs C, H, I, and L) sorted by raw material

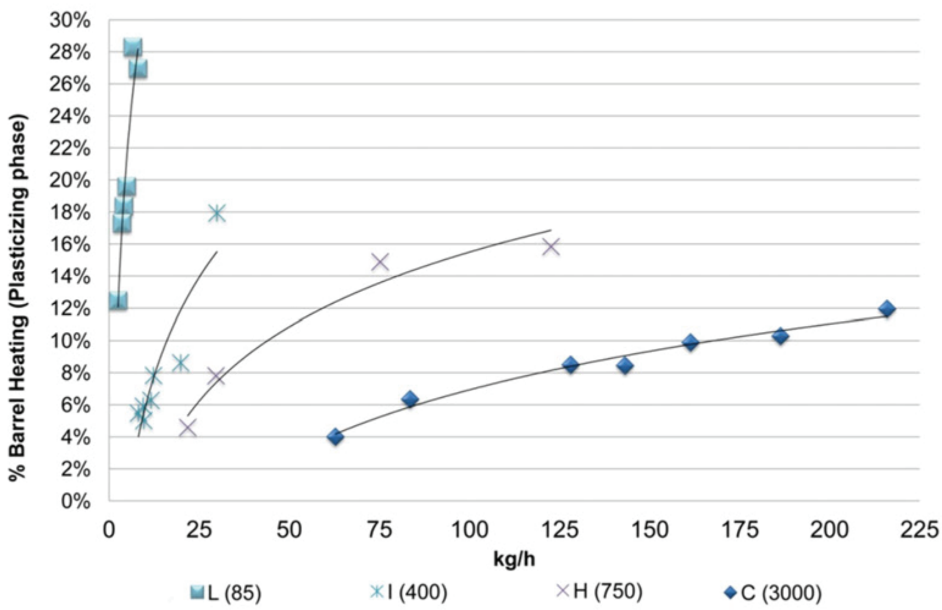

Fig. 9 Percentage of plasticizing phase over the electricity consumption vs. kg/h

remain the same, but the injected thermoplastic is different (PMMA vs. PC). The results show that the electricity consumption of the injection molding process is 7.96% higher for the polycarbonate part than the PMMA part. The viscosity of polycarbonate is higher than the viscosity of PMMA for the high shear rate values (over 10^3 1/s) used in the injection molding process,[38] therefore, the phase of filling the mold and holding would be more energy intensive. On the other hand, the part's geometry (see Fig. 2) has a long flow length and a low thickness (1.5 mm). To reduce the effect of the frozen layer that decreases the effective area for the polymer to flow, which increases the required injection pressure, it is necessary to heat the mold up to temperatures of 100°C in the case of polycarbonate and up to 70°C in the case of PMMA.[39] This fact has a direct influence on the total electric consumption for the process for each part.

As previously stated, along with the movements of the machine, the barrel heating of the plasticizing phase is one of the most intensive phases of the process in terms of energy. To further analyze the results, by applying Eq. (5) to the measurements we can estimate the percentages that this phase has over the total results.

In Fig. 9, different tendencies can be observed for each IMM (the ones that have four or more measurements).

With this estimation, the barrel heating percentage presents values between 4 and 28% of the total SEC, being this percentage smaller as the size of the machine increases (4-12% for "C"). For higher throughputs, the importance of the plasticizing phase increases as the idle times decrease; therefore, the losses, as the capacity of the IMM is better adjusted.

Additionally, it is remarkable that for the two smaller IMMs and overall, for the all-electric machine, this percentage is higher (12-28%) as the power required for the movements is lower given the lower clamping forces and the movements system efficiency.

4.2 Environmental Impact Results and Discussion

The environmental impact of the 36 processes has been calculated using the ReCiPe Endpoint indicator and following the methodology explained in subsection 3.4 "Environmental impact assessment methodology".

The overall impact of the manufacturing of the part can be obtained by assessing the dataset of our functional unit (see section 3.4) taking into consideration its SEC and its gross weight. The results are shown in Table 5.

As can be seen, the results in Table 5 are mostly proportional to the results in Table 4 because the electricity consumption is the most dominant factor in these environmental impact results.[19,20] That is, a reduction in the SEC implies almost the same reduction in the environmental impact of the process. To allow comparisons between parts, as previously shown in subsection 4.1 with the electricity consumption measurements, the results are going to be displayed per kilogram of injected plastic, which is the functional unit of the study (Fig. 10).

The injection molding processes of parts #9 and #31, which are the ones that achieved the highest and lowest values of SEC, are also the ones that have the highest and lowest environmental impact results per kilogram (113.32 vs. 18.03 mPt ReCiPe/kg).

The average environmental impact of the injection of a plastic part with our methodology[20] is 47.7 mPt/kg. Due to the variability of the SEC results, the environmental impact variability is also high (σ = 23.65 mPt ReCiPe/kg, CoV = 49.6%). The average value is 56.7% lower than for the EcoInvent's dataset (111.01 mPt/kg ReCipe), which uses the European electric mix instead of the Spanish electric mix and has broader system limits as previously explained in the methodology section.

The environmental impact results for the all-electric machine (#31-#36) are the lowest with an average of 24.7 mPt ReCiPe/kg. This aspect again shows the high influence that electricity has on the environmental impact.

As also occurred with the electricity consumption, the low range of the environmental impact distribution (0-20 mPt/kg) is only obtained for the processes carried out in the all-electric machine.

However, results lower than average, such as the ones in the range

Table 5 Total Environmental impact of the manufacture of the plastic parts (mPt ReCiPe)

Part number	Weight injected per cycle (g)	mPt ReCiPe/part	Part number	Weight injected per cycle (g)	mPt ReCiPe /part
#1	71800	1469.102	#19	836	27.222
#2	30300	1090.878	#20	1336	80.871
#3	10500	421.654	#21	260	26.497
#4	8700	419.242	#22	310.75	4.048
#5	7258	327.295	#23	288	8.252
#6	4695	256.149	#24	128.58	5.526
#7	3773	204.712	#25	161.24	8.618
#8	1802	129.897	#26	154.12	5.606
#9	1589	180.070	#27	106.00	8.406
#10	646	25.797	#28	100.50	1.045
#11	745	38.961	#29	39.58	2.168
#12	2778	67.510	#30	67.66	0.489
#13	1560	17.654	#31	68.00	0.613
#14	1253	51.264	#32	100.48	0.229
#15	495	24.295	#33	37.00	0.579
#16	489	22.292	#34	16.08	0.214
#17	383	16.300	#35	14.36	0.093
#18	3407	101.745	#36	15.00	0.106

between 20 and 40 mPt/kg, are not only achieved in the all-electric machine but also in hybrid machines. As with the electricity consumption, the majority of the measurements (25 of 36) are in the medium range of the distribution within 20-60 mPt/kg.

On the other hand, the processes with higher impact (> 80 mPt/kg) are the ones with higher SECs regardless of the size of the used IMM.

The already observed descending tendency of the electricity consumption with the throughput is also maintained with the environmental impact, as Fig. 11 shows. Analogously, the environmental impact can differ a lot for the same throughput value, making again the differences between the IMMs relevant.

Due to the direct relationship between the electricity consumption and environmental impact, a high utilization of the machine's capacity also implies a low environmental impact from the injection molding of the plastic parts (Fig. 12). The same conclusions as with the electricity consumption can be drawn by analyzing each part for the

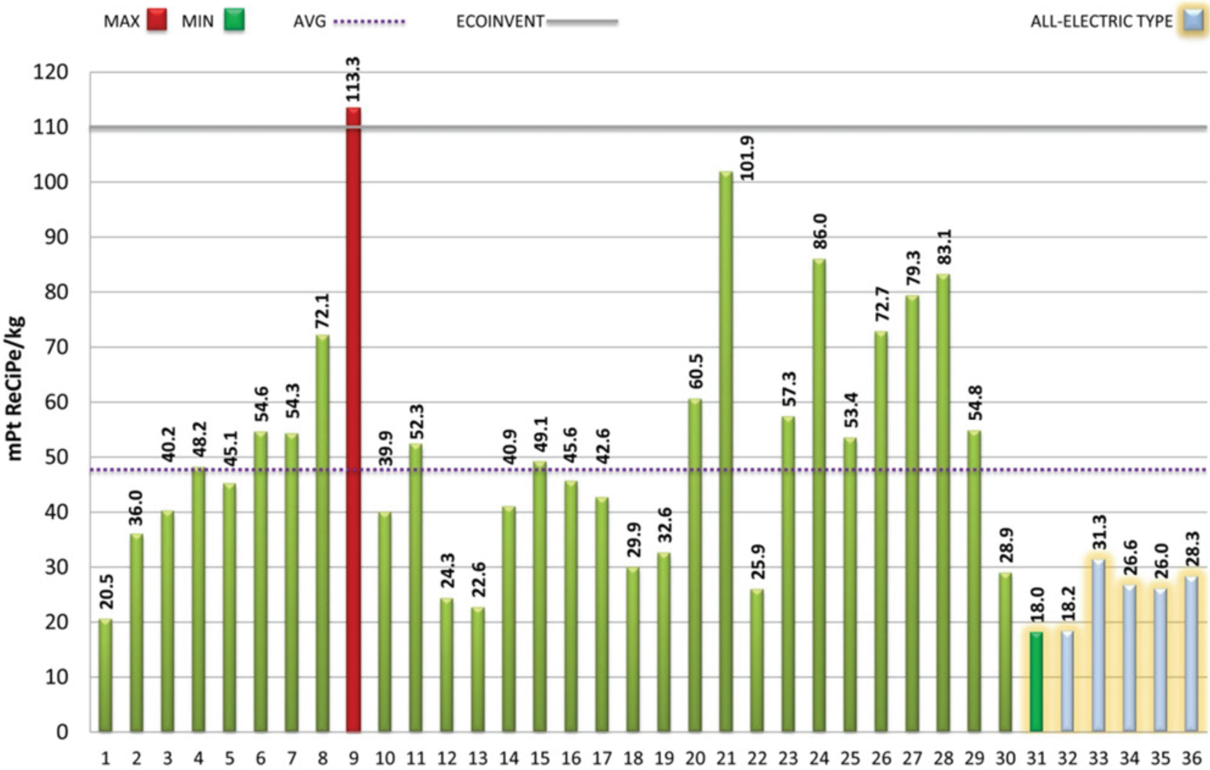

Fig. 10 Environmental impact of the injection of 1 kg of each plastic part

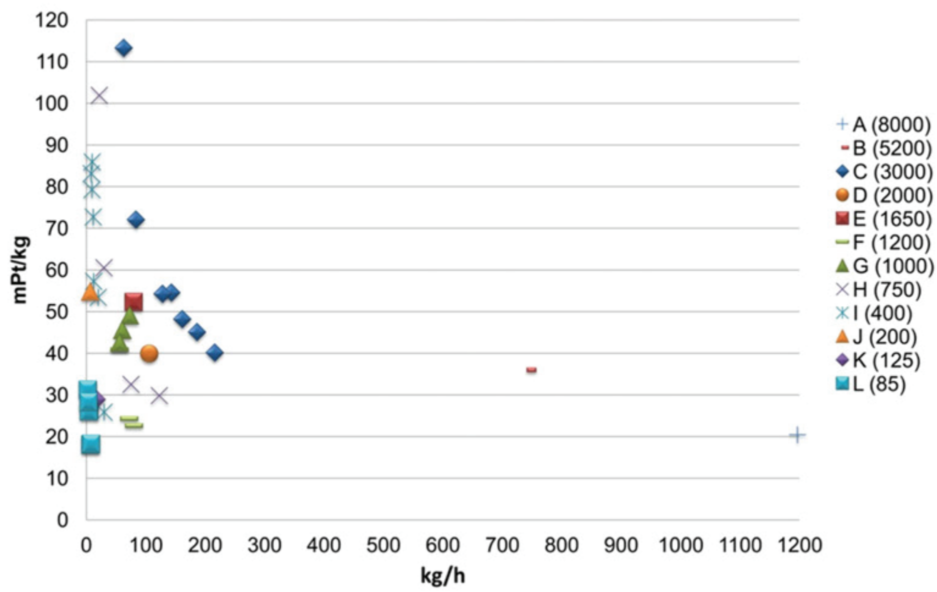

Fig. 11 Environmental impact (mPt ReCiPe/kg) vs. throughput (sorting by IMM)

environmental impact results. For parts #35 and #36, which were injected in the same IMM and have the same geometry, the different raw material makes the environmental impact of the processing of the latter (HDPE part) 8.7% higher. The same occurs with parts #15 and #16, where the processing of the PC registers an environmental impact that is 7.7% higher than for the PMMA's part.

5. Conclusions

The importance of deeply analyzing the energy efficiency of the manufacturing process has been discussed in this study. Better knowledge is required in order to identify potential improvements that allow for reducing the electricity consumption along with the related cost and the environmental impact of manufacturing companies.

The electricity consumption of several IMMs has been analyzed by monitoring the electricity consumption of 36 different case studies. The obtained results have shown how the type of machine influences the electricity consumption. As indicated by Knights,[29] who indicated a possible range of 30-70% in energy savings, it is quite remarkable the savings that were achieved by the studied all-electric machine (54.4%) in comparison with the other equipment for our measurements (0.529 kWh/kg of average SEC for the all-electric machine versus 1.161 kWh/kg for the rest of the IMMs). The average SEC for all the case studies is 1.06 kWh/kg, which is 27.8% lower than the statistic value used by the EcoInvent database. These SEC measurements have high variability (CoV: 51.4%), and the maximum and minimum consumption values were achieved by processing parts #9 and #31 (2.563 and 0.375 kWh/kg, respectively). Part #9 was injected into a 3000 ton hybrid IMM and it used less than the 9% of its total capacity. On the other hand, part #31 was manufactured in an 85 ton all-electric IMM at almost its full capacity.

The importance of the high utilization of the IMM's capacity has also been highlighted. With high percentages of utilization, the SEC of the injection molding process is minimized. Together with the machine's movements, the plasticizing phase is one of the most energy intensive phases. It has been observed how the percentage of the total SEC that this phase uses rises as the throughput increases. Additionally, its influence is higher for smaller machines because the energy demand of the machine's drivers is lower; therefore, the energy consumption percentage caused by the barrel heating is higher, so actions to reduce the heating losses would be more effective in these cases.

These electricity consumption measurements have been used to characterize the environmental impact of the manufacturing of the analyzed parts given the high influence that the electricity consumption has on this process. An average of 47.7 mPt ReCiPe/kg is obtained for all of the case studies (57% lower than EcoInvent's database value) with parts #9 and #31 being the parts with the maximum and minimum values (113.32 and 18.03 mPt ReCiPe/kg).

Although there is also a high variability in the results, the clear correlation between a high utilization of the IMM and the low environmental impact of the process is kept as it happens with the electricity consumption.

Although the lack of data present in some of the studies mentioned in the state of the art review makes it difficult, and in some cases impossible, to make comparisons, the results from this work can be compared to some of them, revealing similarities and differences. For example, the most similar parts in weight in our study compared to the measurements performed by Lechner[30] are parts #27, #28 and #32, which have higher SEC values in our study (1.78, 1.86 and 0.38 kWh/kg, respectively). The differences are caused by higher cycle times (more than double) and therefore lower throughputs and used capacity. Regardless the increase in productivity the importance of reducing the cycle time by optimizing the process's parameters or via design, e.g., reducing the parts thickness, are very relevant.

On the other hand, the measurements presented by Spiering et al.[18]

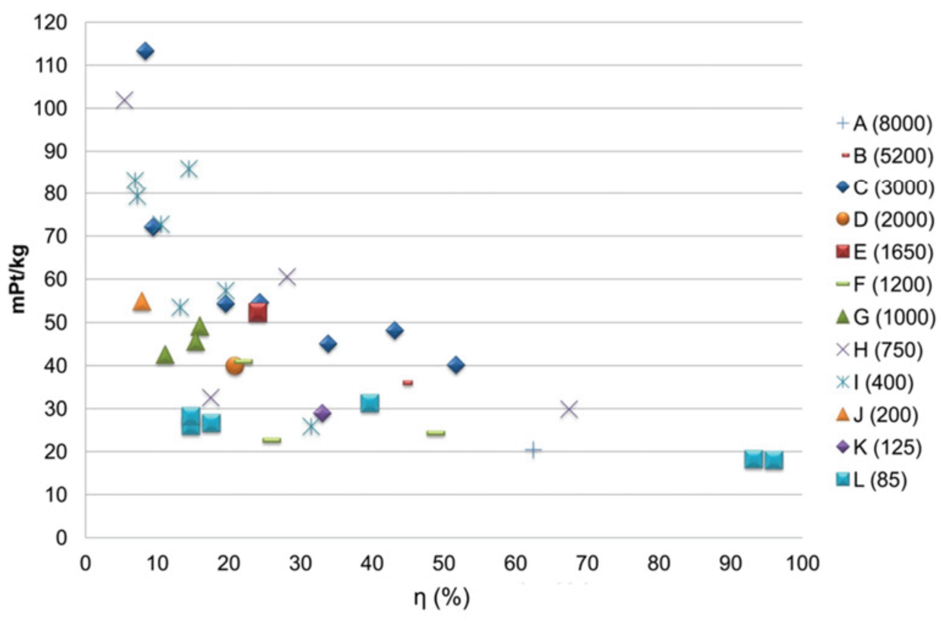

Fig. 12 Environmental impact (mPt ReCiPe/kg) vs. η (sorting by IMM)

do not allow for individual comparisons because they are all gathered in one graph without indicating the values. The correlation value of all of their measurements is 0.7 (including several IMMs and materials). Most of our analyses have been carried out by clustering measurements, which resulted in correlation values greater than 0.875.

Part #7 in our study has similar characteristics to the one presented by Spiering et al.,[18] mentioned in the state of the art review. Part #7 has an SEC of 1.2 kWh/kg (22.6% lower than Spiering's), which could point out that either the throughput is higher for our case or the machine's capacity or technology is more optimized. Additionally, the quantity and type of filler (talc versus glass fiber) could have some influence. The knowledge that these kind of measurements gives to the companies could be used not only to assess their environmental footprint but also for energy and cost reduction purposes by using these measurements as an internal benchmark. The variability observed in the previous research from the authors is again present incorporating measurements with more different raw materials and IMMs, this variability should be taken into account by LCA practitioners while analyzing the injected plastic parts. Engineers should consider actions such as reducing the cycle time of the process without risking the product's quality or the use of a more adjusted machine according to the part's dimensions to achieve lower SEC values. Another factor to take into account is that materials with high viscosity or filled tend to register higher energy consumption values making this aspect especially relevant for parts with low thicknesses.

Additionally, manufacturers are encouraged to invest in all-electric machines instead of in hydraulic or hybrid machinery because their performance would always be more efficient. Although in the past these machines were limited in their characteristics, technology has been evolving, and electric IMMs of up to 3500 tons of clamping force are available in the market making them big enough to manufacture most plastic parts.[40]

There is further research potential that should be carried out to overcome the limitations of this study. Other injection technologies such as Mucell or gas injection could be analyzed by following the procedure used in this paper. If possible, the measurement of the electricity consumption of each IMM subsystem could contribute to further comprehending the relationships between the part, IMM, parameters and total electricity consumption. More measurements of the same mold with different raw materials or injected in different IMMs could be performed to further independently analyze the influence of these parameters.

It could also be interesting to expand the number of analyzed materials, measuring plastic parts made of PVC, or other common thermoplastics such as PET, that are not covered in this study. Moreover, how the percentage of filler, such as glass fiber, influences the electricity consumption of the same part could contribute to the knowledge of this topic.

All these research lines could enable the design of plastic parts and their molds in the future by taking into account factors such as the available IMMs and considering the design actions such as the definition of thickness, flow length, number of gates or cooling to develop the most efficient combination considering the process and industry constraints.

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REFERENCES

1. Dornfeld, D. A., "Moving towards Green and Sustainable Manufacturing," Int. J. of Precis. Eng. Manuf.-Green Tech., Vol. 1, No. 1, pp. 63-66, 2014.
2. Martínez, E., Jiménez, E., Blanco, J., and Sanz, F., "LCA Sensitivity Analysis of a Multi-Megawatt Wind Turbine," Applied Energy, Vol. 87, No. 7, pp. 2293-2303, 2010.
3. Ricciardi, P., Belloni, E., and Cotana, F., "Innovative Panels with Recycled Materials: Thermal and Acoustic Performance and Life Cycle Assessment," Applied Energy, Vol. 134, pp. 150-162, 2014.
4. Nam, S., Lee, D. K., Jeong, Y.-K., Lee, P., and Shin, J.-G., "Environmental Impact Assessment of Composite Small Craft Manufacturing Using the Generic Work Breakdown Structure," Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 3, No. 3, pp. 261-272, 2016.
5. Elduque, D., Javierre, C., Pina, C., Martínez, E., and Jiménez, E., "Life Cycle Assessment of a Domestic Induction Hob: Electronic Boards," Journal of Cleaner Production, Vol. 76, pp. 74-84, 2014.
6. Kabakian, V., McManus, M., and Harajli, H., "Attributional Life Cycle Assessment of Mounted 1.8 kWp Monocrystalline Photovoltaic System with Batteries and Comparison with Fossil Energy Production System," Applied Energy, Vol. 154, pp. 428-437, 2015.
7. Chiarini, A., "Sustainable Manufacturing-Greening Processes Using Specific Lean Production Tools: An Empirical Observation from European Motorcycle Component Manufacturers," Journal of Cleaner Production, Vol. 85, pp. 226-233, 2014.
8. Weinert, N., Chiotellis, S., and Seliger, G., "Methodology for Planning and Operating Energy-Efficient Production Systems," CIRP Annals-Manufacturing Technology, Vol. 60, No. 1, pp. 41-44, 2011.
9. Luo, H., Du, B., Huang, G. Q., Chen, H., and Li, X., "Hybrid Flow Shop Scheduling Considering Machine Electricity Consumption Cost," International Journal of Production Economics, Vol. 146, No. 2, pp. 423-439, 2013.
10. He, Y., Li, Y., Wu, T., and Sutherland, J. W., "An Energy-Responsive Optimization Method for Machine Tool Selection and Operation Sequence in Flexible Machining Job Shops," Journal of Cleaner Production, Vol. 87, pp. 245-254, 2015.

11. Mativenga, P. and Rajemi, M., "Calculation of Optimum Cutting Parameters Based on Minimum Energy Footprint," CIRP Annals-Manufacturing Technology, Vol. 60, No. 1, pp. 149-152, 2011.

12. Lee, W., Lee, C.-Y., and Min, B.-K., "Simulation-Based Energy Usage Profiling of Machine Tool at the Component Level," Int. J. Precis. Eng. Manuf.-Green Tech., Vol. 1, No. 3, pp. 183-189, 2014.

13. Behrendt, T., Zein, A., and Min, S., "Development of an Energy Consumption Monitoring Procedure for Machine Tools," CIRP Annals-Manufacturing Technology, Vol. 61, No. 1, pp. 43-46, 2012.

14. Avram, O. I. and Xirouchakis, P., "Evaluating the Use Phase Energy Requirements of a Machine Tool System," Journal of Cleaner Production, Vol. 19, No. 6, pp. 699-711, 2011.

15. Kara, S. and Li, W., "Unit Process Energy Consumption Models for Material Removal Processes," CIRP Annals-Manufacturing Technology, Vol. 60, No. 1, pp. 37-40, 2011.

16. Europe, P., "Plastics-The Facts 2014/2015 an Analysis of European Plastics Production, Demand and Waste Data," Plastic Europe, 2015.

17. Deng, J., Li, K., Harkin-Jones, E., Price, M., Karnachi, N., et al., "Energy Monitoring and Quality Control of a Single Screw Extruder," Applied Energy, Vol. 113, pp. 1775-1785, 2014.

18. Spiering, T., Kohlitz, S., Sundmaeker, H., and Herrmann, C., "Energy Efficiency Benchmarking for Injection Moulding Processes," Robotics and Computer-Integrated Manufacturing, Vol. 36, pp. 45-59, 2015.

19. Elduque, A., Javierre, C., Elduque, D., and Fernández, Á., "LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process," Sustainability, Vol. 7, No. 4, pp. 3792-3800, 2015.

20. Elduque, A., Elduque, D., Javierre, C., Fernández, Á., and Santolaria, J., "Environmental Impact Analysis of the Injection Molding Process: Analysis of the Processing of High-Density Polyethylene Parts," Journal of Cleaner Production, Vol. 108, pp. 80-89, 2015.

21. Uluer, M. U., Unver, H. O., Gok, G., Fescioglu-Unver, N., and Kilic, S. E., "A framework for Energy Reduction in Manufacturing Process Chains (E-MPC) and a Case Study from the Turkish Household Appliance Industry," Journal of Cleaner Production, Vol. 112, pp. 3342-3360, 2016.

22. Thiriez, A. and Gutowski, T., "An Environmental Analysis of Injection Molding," Proc. of in IEEE International Symposium on Electronics and the Environment, pp. 195-200, 2006.

23. Kitayama, S. and Natsume, S., "Multi-Objective Optimization of Volume Shrinkage and Clamping Force for Plastic Injection Molding via Sequential Approximate Optimization," Simulation Modelling Practice and Theory, Vol. 48, pp. 35-44, 2014.

24. Wang, Y., Yu, K.-M., and Wang, C. C., "Spiral and Conformal Cooling in Plastic Injection Molding," Computer-Aided Design, Vol. 63, pp. 1-11, 2015.

25. Nian, S.-C., Tsai, S.-W., Huang, M.-S., Huang, R.-C., and Chen, C.-H., "Key Parameters and Optimal Design of a Single-Layered Induction Coil for External Rapid Mold Surface Heating," International Communications in Heat and Mass Transfer, Vol. 57, pp. 109-117, 2014.

26. Wang, G., Zhao, G., and Wang, X., "Development and Evaluation of a New Rapid Mold Heating and Cooling Method for Rapid Heat Cycle Molding," International Journal of Heat and Mass Transfer, Vol. 78, pp. 99-111, 2014.

27. Lu, N.-Y., Gong, G.-X., Yang, Y., and Lu, J.-H., "Multi-Objective Process Parameter Optimization for Energy Saving in Injection Molding Process," Journal of Zhejiang University-Science A, Vol. 13, No. 5, pp. 382-394, 2012.

28. Park, H. S. and Nguyen, T. T., "Optimization of Injection Molding Process for Car Fender in Consideration of Energy Efficiency and Product Quality," Journal of Computational Design and Engineering, Vol. 1, No. 4, pp. 256-265, 2014.

29. Plastics Technology, "Electric, Hydraulic, or Hybrid? What's the Right Injection Press for You?" https://www.ptonline.com/articles/electric-hydraulic-or-hybrid-what's-the-rightinjection-press-for-you (Accessed 22 DEC 2017)

30. Plastics Technology, "Advantages of Servo-Driven Hydraulics For Large Injection Machines," https://www.ptonline.com/articles/advantages-of-servo-driven-hydraulics-for-large-injection-machines (Accessed 22 DEC 2017)

31. Hischier, R., "Part II Plastics. Life Cycle Inventories of Packaging and Graphical Papers. Ecoinvent-Report No. 11," Swiss Centre for Life Cycle Inventories, 2007.

32. Goedkoop, M., Oele, M., Leijting, J., Ponsioen, T., and Meijer, E., "Introduction to LCA with SimaPro," PRé, Amersfoort, 2016.

33. Dong, Y. H. and Ng, S. T., "Comparing the Midpoint and Endpoint Approaches Based on Recipe-A Study of Commercial Buildings in Hong Kong," International Journal of Life Cycle Assessment, Vol. 19, No. 7, pp. 1409-1423, 2014.

34. Tan, Y. S., Tjandra, T. B., and Song, B., "Energy Efficiency Benchmarking Methodology for Mass and High-Mix Low-Volume Productions," Procedia CIRP, Vol. 29, pp. 120-125, 2015.

35. Franck, A., "Understanding Rheology of Thermoplastic Polymers," TA Instruments, 2004.

36. Klein, R., "Laser Welding of Plastics," John Wiley & Sons, 2012.

37. Ribeiro, I., Peças, P., and Henriques, E., "A Life Cycle Framework to Support Materials Selection for Ecodesign: A Case Study on Biodegradable Polymers," Materials & Design, Vol. 51, pp. 300-308, 2013.

38. Goodship, V. and Love, J., "Multi-Material Injection Moulding," iSmithers Rapra Publishing, 2002.

39. Uluer, O., "The Effect of the Processing Parameters on Frozen Layer Formation in Injection Molding," Journal of the Faculty of Engineering and Architecture of Gazi University, Vol. 23, No. 1, pp. 249-255, 2008.

40. U-MHI PLATECH Co., Ltd., http://www.u-mhipt.co.jp/injec_e/products/em1050-1600/index.htm (Accessed 22 DEC 2017)

Article

Empirical Model to estimate the Electricity Consumption of the Polymer Material Injection Molding Manufacturing Process

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Abstract: Polymer injection moulding is one of the most used manufacturing processes in the industry. Material and electricity consumption are two of the main points when analyzing the cost and also the environmental impact of these manufacturing processes. Reducing both cost and environmental impact of materials and manufacturing processes is one of the key challenges that material science and engineering face today to be more sustainable. In the case of the polymer injection moulding manufacturing process, reducing its electricity consumption is key to achieve a more sustainable manufacturing process. However, a lack of data regarding real electrical consumption values, and how to estimate them has been found. In this paper, a model to estimate the electric consumption of the injecting molding manufacturing process is proposed. This consumption estimation is obtained by means of a parametric model which was created after monitoring the electricity consumption of a wide range of injected parts. By applying this empirical model a better assessment of the electricity consumption, and also the environmental impact of the process can be achieved. This model can be of great interest for manufacturing process engineers, Life Cycle Assessment practitioners and also the industry, as it provides a method to estimate the electricity consumption and cost of an injected part depending on its characteristics and the selected injection machine.

Keywords: Polymer material; Manufacturing processes; Electricity consumption, Environmental impact, Empirical model

PACS: J0101

1. Introduction

Climate change is forcing companies to perform risk management and also to look for opportunities in the path of reducing the environmental impact of their activities [1-2].

The concern regarding the achievement of a sustainable development is also patent in the literature. Strategies to achieve a cleaner industrial sector are discussed by using, for example, analytical tools that help in the decission making of an industrial process [3], or linking lean manufacturing practices with the lifecycle assessment methodology in order to obtain a reduction of the environmental impact [4].

Polymer injection moulding is a common manufacturing process with high volumes in the industry [5]. Reduction of its environmental impact would be an important step to achieve a more sustainable development.

As discussed in previous work made by the authors, the electricity consumption of the injection molding process is the main factor in the total environmental impact of this process [6,7]. Due to this, achieving a reduction of the electricity consumption not only affects directly to the environmental footprint but also to the economic cost.

Therefore, injection molding producers should have as a goal to have a deeply knowledge of their machines in order to be able to optimize their consumption, obtaining at the same time these two important benefits. LCA studies have been performed to very different products and processes in all work fields, to assess its environmental impact [8-11]. Increasing the knowledge about the injection molding process leads to an improvement also in the LCA field, as databases, such as EcoInvent, that are used in the Life Cycle Inventory phase, are key in the results obtained in LCA studies.

EcoInvent's dataset injection molding process is created calculating the average of three processes: PVC, PP and PET, and consider for the environmental impact assessment, in addition to electricity consumption (1,47 kWh/kg as mean value), consumption of water, lubricating oils, chemicals, fillers, solvents, packaging materials, natural gas for the factory, generated waste...etc. [12]. However, as previously explained, the highest contribution to the environmental impact is caused by the electricity consumption [6,7].

Not so many studies with experimental data of injection molding and its electricity consumption can be found yet in the literature. An interesting study of monitoring energy was published by Mianehrow and Abbasian [13] where they analyzed how different factors such as machine technology, or process related parameters affect the electricity consumption, being the cycle time and throughput one of the most important. More studies have been published in the recent years regarding the environmental impact of the injection molding process. Thiriez reviewed the complete process including the compounding of the raw material. In this research it is indicated that the type of injection molding machine has a great impact in the electricity consumption of the process, as it will be seen in this paper [14]. Other authors focused their research in the environmental performance of biodegradable polymers [15,16]. Studies concerning the estimation of the electricity consumption of the injection molding process have been carried out using a theoretical approach instead of experimental, like the one used in this paper [17,18]. Spiering et al. remarked the importance of analyzing deeply the life cycle inventories also in the manufacturing processes [19].

In this research work, results from experimental measurements have been analyzed in order to define a parametric model that allows to estimate the electricity consumption of an specific injection molding process. By means of this empirical model a more precise value can be obtained to further assess the environmental impact and also the cost related to this manufacturing process.

2. Materials and Methods

As the purpose of this paper was to obtained a mathematical model, only a calculation sheet has been used to analyze the experimental data. Many tendencies have been observed and studied. As indicated by the authors in the paper "Influence of Material and Injection Molding Machine's Selection on the Electricity Consumption and Environmental of the Injection Molding Process: An Experimental Approach" [20], several conclusions can be drawn from the 36 experimental measurements.

One of the most important tendencies is that the more throughput (kg/h) the process has, the less SEC is obtained by the injected part. On the other hand, each injection molding machine shows a different tendency, as their technology and efficiency are different.

Twelve different injection molding machines were analyzed in these measurements: from a 2002 all-electric injection machine, with a clamping force of 85 tonnes, to the largest injection molding machine (8000 tonnes of clamping force).

2.1. Parameters

The parameters that have been selected to build this empirical model are the following:

- Percentage of the machine's utilization: relation between part injected volume and maximum volume that can be injected in one shot
- Machine's efficiency
- Throughput (kg/h)
- Polymer material (Specific heat [KJ/kg.K] x ΔT)

With these four parameters it is being included the influence of injection molding machine (its technology), how well it is the machine and process optimized and the properties of the polymer material.

A total of 36 measurements were used using different thermoplastics such as high density polyethylene, polypropylene, polycarbonate, polyamide with several percentages of fillers, etc. Further details regarding parts injected and measurement equipment to obtain real consumption values can be consulted in previous published work by the authors [20].

3. Results and Discussion

In the following section it is going to be explained how the empirical model is built, and the obtained results.

3.1. Empirical Model

Two steps were performed to adjust the empirical model. First electricity consumption was modeled considering the percentage of utilization and machine's efficiency. Figure 1 shows all experimental measurements in blue dots used for creating the empirical model. The low, medium and high efficiency lines, show the limits of the SEC depending on the efficiency of the injection machine.

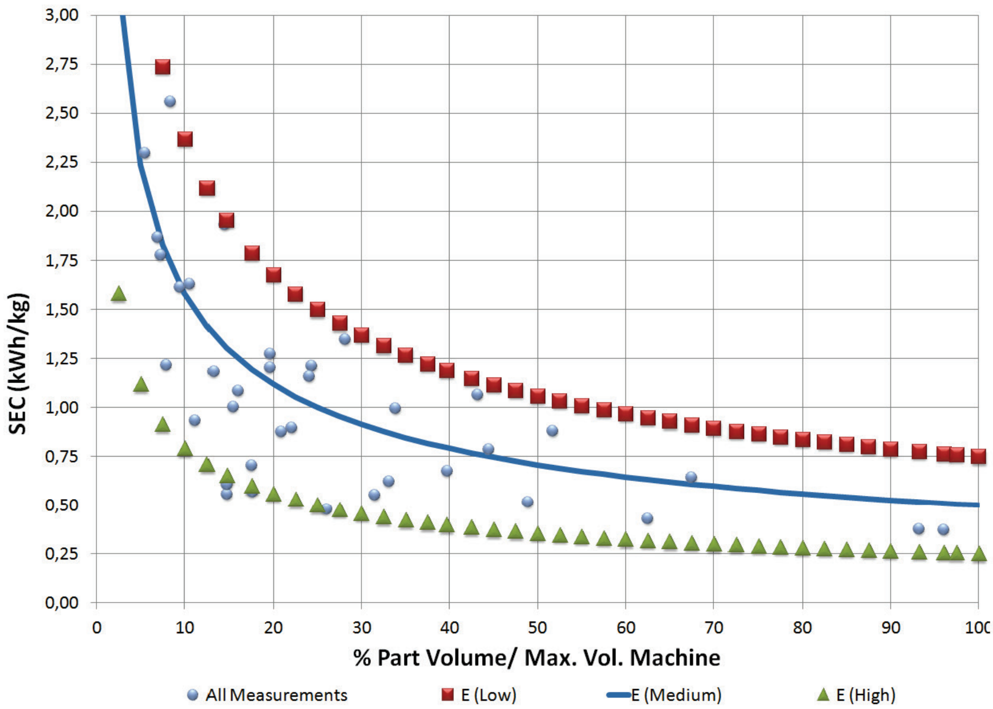

Figure 1. Empirical model.

Table 1 shows the electricity consumption values estimated by the model for the three cases shown in Figure 1, low efficiency machine, medium and high.

Table 1. Estimated electricity consumption in KWh/kg for different values of machine efficiency and % of utilization

% of utilization	Low Efficiency	Medium Efficiency	High Efficiency
0	6,000	5,000	4,000
10	2,372	1,581	0,791
20	1,677	1,118	0,559
30	1,369	0,913	0,456
40	1,186	0,791	0,395
50	1,061	0,707	0,354
60	0,968	0,645	0,323
70	0,896	0,598	0,299
80	0,839	0,559	0,280
90	0,791	0,527	0,264
100	0,750	0,500	0,250

Values from Table 1 are obtained with Equation 1:

$$SEC\ (KWh/kg) = (7{,}5 - 5.\ E/100)\ .\ (\eta)^{0{,}5} \quad (1)$$

where E is the efficiency of the injection machine, and η, the percentage of utilization of the injection molding machine. η is defined as Equation 2 indicates:

$$\eta = w.100/\rho.\ V_{max} \quad (2)$$

where w is the part's weight in grams, ρ is the density of the polymer material (g/cm^3) and V_{max} is the maximum value that the injection molding machine is able to inject (cm^3).

Value for 0% of utilization is included as a reference, as it cannot be infinite.

In this second step, a better adjustment is obtained modifying the considered efficiency with two correction factors. The first one is related with the throughput of the process. A higher throughput will lead to a more optimized process (higher value of efficiency and lower electricity consumption). An empirical value has been calculated to estimate the average throughput depending on the clamping force of the injection molding machine (Equation 3).

$$\text{Average Throughput (kg/h)} = 0{,}051.\ \text{Clamping Force (Tonnes)} \quad (3)$$

This way the correction factor of the throughput (CFT) will be defined as (Equation 4):

$$CFT = (w.3{,}6/t_c)\ /\ 0{,}051.\ F_c\ (\text{Tonnes}) \quad (4)$$

being t_c, the cycle time in seconds.

In Equation 5 is defined the second factor that adds the influence of the polymer material (CFP).

$$CFP= (c_e.(T_i-T_a))/350,255 \tag{5}$$

Using the specific heat of the polymer material (c_e) and the difference between injection temperature (T_i) and ambient temperature (T_a). The "350,255" is an experimental value obtained as an average of the factor $c_e.(T_i-T_a)$ in the measurements.

So, finally, the modified machine's efficiency, E', that replaces E in Equation 1, is defined including it in the model with Equation 6:

$$E' = E\ .\ (CFT)^{0,15} / (CFP)^{0,1} \tag{6}$$

where the influence of the throughput is higher than the one of the polymer material.

The considered efficiency for each injection molding machine was selected considering their technology and manufacturing date as the Table 2 shows.

Table 2. Machine's efficiency for the empirical model, E

Injection Molding Machine	Clamping force (Tn)	Manufacturing date	Efficiency (E)
A	8000	2005	70
B	5200	2005	70
C	3000	2000	65
D	2000	2010	75
E	1650	2010	75
F	1200	1999	65
G	1000	2008	70
H	750	2005	70
I	400	1996	60
J	200	1999	65
K	125	1999	65
L	85 (All-electric)	2002	100

Taking all this into account, the final equation of the empirical model is shown in Equation 7:

$$SEC = (7,5- (5.\ (E/100).(((w.3,6/t_c)/(0.051.\ F_c))^{0,15}/(c_e.(T_i - T_a)/350,255)^{0,1})))\ .\ (w.100/(\rho.\ V_{max}))^{0,5} \tag{7}$$

In Figure 2, the model's results are displayed comparing real measurement data with the estimation of the empirical model and the EcoInvent's value for the electricity consumption of the injection molding process for 1kg of thermoplastic.

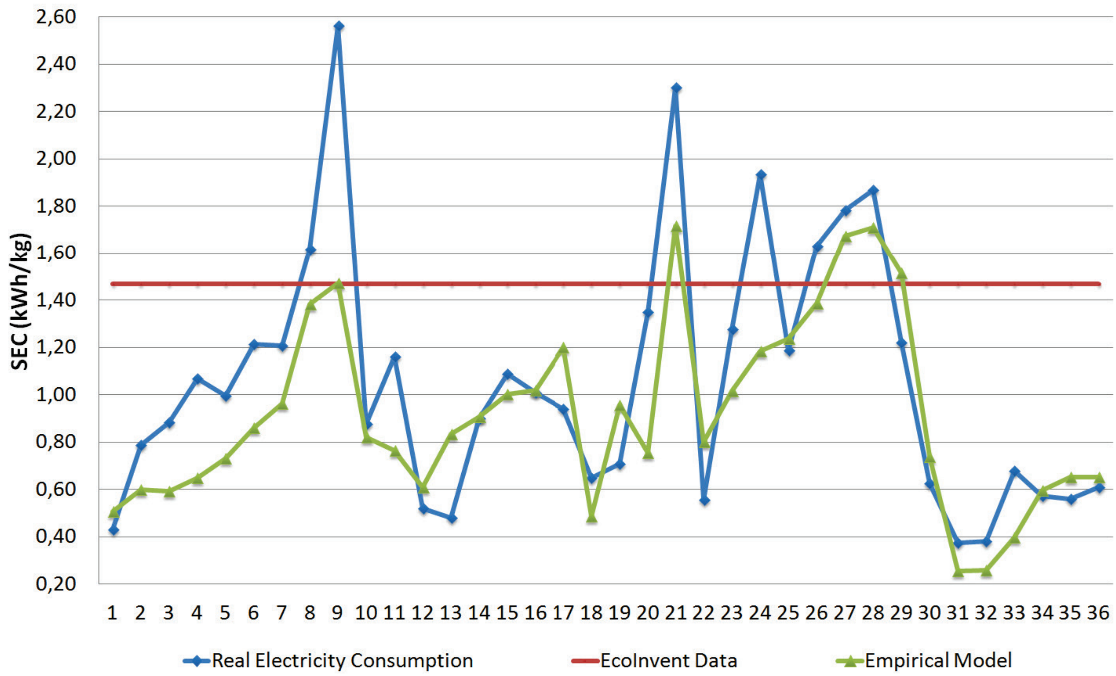

Figure 2. Comparison of Model's results, real data values and EcoInvent's

An average of absolute error of a 22,5% is obtained with the empirical model lower than the 86,8% absolute error obtained using EcoInvent's value for this set of measured parts.

Part #9 register the maximum error in this empiric model. This part was injected in one of the largest machines (C), it has a high thickness and during its process it required a high cycle time for its processing which lead to a low kg/h value. In addition, the η is very low. As it can be seen in Figure 1, for low values of utilization, the model's uncertainty increases, as the electric consumption result is much more sensitive to changes in E' value.

4. Conclusions

By using the proposed model in this paper, a better estimation of the electricity consumption can be achieved. Databases such as EcoInvent provide an average value for the injection molding process electricity consumption (1,47 kWh/kg). Considering this value as a constant of every injected molded part leads to an error due to that variability in this process is very high, as experimental measurements revealed depending on polymer material, injection molding machine and process's parameters. Our empirical model obtains an average absolute error of 22.5%, much lower than the 86.8% obtained when using EcoInvent´s data.

As future research directions, increase the number of experimental measurements with other injection molding machines with different clamping forces and technologies could help to improve the estimation obtained with the empirical model.

Also as each injection molding machine seem to have a unique profile of electricity consumption, to carry out a benchmarking of the plant machinery is an important step to be made by plastic producers and characterize correctly the machine's efficiency.

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Author Contributions: A.Elduque contributed to the study carrying out partially the experimental measurements shown in the study, reviewing the state of art, analyzing the experimental data to propose the empirical model and writing the paper, D.Elduque performed partly the experimental measurements, contributing to the adjustment of the model and revising the paper; I. Clavería and C Javierre. contributed to give structure to the paper, and adjust the empirical model analyzing the data and drawing conclusions.

Conflicts of Interest: The authors declare no conflict of interest.

Abbreviations

The following abbreviations are used in this manuscript:

CFP: Correction Factor of the Polymer material
CFT: Correction Factor of the Throughput
LCA: Life Cycle Assessment
SEC: Specific Electricity Consumption (unit in kWh/kg)

References

1. Elijido-Ten, E.O.; Clarkson, P. Going Beyond Climate Change Risk Management: Insights from the World's Largest Most Sustainable Corporations. *J Bus Ethics*, **2017**, 1-23, https://doi.org/10.1007/s10551-017-3611-6.
2. Dornfeld, D. Moving towards Green and Sustainable Manufacturing. *Int J. of Precis. Eng. Manuf.-Green Tech.*, **2014**, *1*, 63-66, https://doi.org/10.1007/s40684-014-0010-7.
3. Correa, M.; Pawlowsky, U.; Scurupa, K. Environmental performance evaluation - A proposed analytical tool for an industrial process application. *J Clean Prod.* **2018**, *20*, 1452-1464, https://doi.org/10.1016/j.jclepro.2017.10.289.
4. Cheung, W. M.; Leong, J. T.; Vichare, P. Incorporating lean thinking and life cycle assessment to reduce environmental impacts of plastic injection moulded products. *J Clean Prod.* **2017**, *167*, 759-775, https://doi.org/10.1016/j.jclepro.2017.08.208.
5. PlasticsEurope, Association of Plastic Manufacturers. Plastics- the Facts 2017, An analysis of European plastics production, demand and waste data. **2018** , Brussels. Available online URL: https://www.plasticseurope.org/en/resources/publications/274-plastics-facts-2017
6. Elduque, A., Javierre, C., Elduque, D. and Fernández, Á. LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process. *Sustainability*, **2015**, *7*, 3792-3800, http://www.mdpi.com/2071-1050/7/4/3792.
7. Elduque, A., Elduque, D., Javierre, C., Fernández, Á. and Santolaria, J., Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts. *J Clean Prod*, **2015**, *108*, 80-89, https://doi.org/10.1016/j.jclepro.2015.07.119.
8. Medeiros, D.L.; Tavares, A.O..C.; Rapôso, Á.L.Q.; Rapôso,S.; Kiperstok, A. Life cycle assessment in the furniture industry: the case study of an office cabinet. *Int J Life Cycle Assess.* **2017**, *22*, 1823-1836, https://doi.org/10.1007/s11367-017-1370-3.
9. Jiménez, E.; Martínez, E.; Blanco, J.; Pérez, M.; Graciano, C. Methodological approach towards sustainability by integration of environmental impact in production system models through life cycle analysis: Application to the Rioja wine sector. *SIMULATION*, **2014**, *90(2)*, 143-161, https://doi.org/10.1177/0037549712464409
10. Finnegan, W.; Yan, M.; Holden, N.M.; Goggins, J. A review of environmental life cycle assessment studies examining cheese production. *Int J Life Cycle Assess.* **2017**, 1-15, https://doi.org/10.1007/s11367-017-1407-7.
11. Simone Souza, H.H.; Lima, Â.M.F.; Esquerre, K.O.; Kiperstok, A. Life cycle assessment of the environmental influence of wooden and concrete utility poles based on service lifetime. *Int J Life Cycle Assess.* **2017**, *22*, 2030-2041, https://doi.org/10.1007/s11367-017-1293-z.
12. Hischier, R. Part II Plastics. Life Cycle Inventories of Packaging and Graphical Papers. Ecoinvent- report Nº 11. *Swiss Centre for Life Cycle Inventories*, **2007**, Dübendorf.
13. Mianehrow, H.; Abbasian, A. Energy monitoring of plastic injection molding process running with hydraulic injection molding machines. *J Clean Prod.* **2017**, *148*, 804-810, https://doi.org/10.1016/j.jclepro.2017.02.053.
14. Thiriez, A. An Environmental Analysis of Injection Molding. *Master of Science in Mechanical Engineering*. **2006**, Massachussets Institute of Technology.

15. Ribeiro, I.; Peças, P.; Henriques, E. A life cycle framework to support materials selection for Ecodesign: A case study on biodegradable polymers. *Mater. Des.* **2013**, *51*, 300-308, https://doi.org/10.1016/j.matdes.2013.04.043.
16. Almeida, D. Life Cycle Engineering approach to analyze the performance of biodegradable injection moulding plastics, **2011**, Instituto Superior Técnico, Universidade Técnica de Lisboa.
17. Weissman, A.; Gupta, S. K.; Ananthanarayanan, A.; Sriram, R. D. A systematic methodology for accurate design-state estimation of energy consumption for injected molded parts. **2010**, Montreal,Quebec.
18. Madan J.; Mani, M.; Lee, J.H.; Lyons K.W. Energy performance evaluation and improvement of unit-manufacturing processes: injection molding case study. *J Clean Prod.* **2015**, *105*, 157-170, https://doi.org/10.1016/j.jclepro.2014.09.060
19. Spiering, T.; Kohlitz, S.; Sundmaeker, H.; Herrmann, C. Energy efficiency benchmarking for injection moulding processes. *Robot Cim- Int Manuf*, **2015**, *36*, 45-59, https://doi.org/10.1016/j.rcim.2014.12.010
20. Elduque, A.; Elduque, D.; Clavería, I.; Javierre, C. Influence of Material and Injection Molding Machine's selection on the electricity consumption and environmental impact of the injection molding process: an experimental approach. *Int. J. of Precis Eng. Manuf.-Green Tech.* **2018**, *5*, 13-28, https://doi.org/10.1007/s40684-018-0002-0.

Capítulo 10

ANEXOS

10. ANEXOS

10.1. APÉNDICE PUBLICACIONES CIENTÍFICAS

LCI Databases Sensitivity Analysis of the Environmental Impact of the Injection Molding Process, [101], (Apartado 9.1)

- Factor de impacto: 1,343
- Categoría: Q3, 62/104, Environmental Studies
- Contribución del doctorando: Revisión del estado del arte. Procesado de los datos y cálculos de impacto ambiental realizados con el software SimaPro. Redacción y corrección del artículo en inglés.

Environmental impact analysis of the injection molding process: analysis of the processing of high-density polyethylene parts, [102], (Apartado 9.2)

- Factor de impacto: 4,959
- Categoría: Q1, 16/225, Environmental Sciences
- Contribución del doctorando: Revisión del estado del arte. Planteamiento de la metodología y cálculo de impacto ambiental con el software SimaPro. Realización de medidas experimentales. Cálculo de resultados e interpretación. Redacción y corrección del artículo en inglés.

LCA Software for Environmental Impact Assessment of Injected Mould Plastic Parts, [103], (Apartado 9.3)

- Factor de impacto/Categoría: Publicación en proceedings del congreso, publicados en Scopus, por lo que no se clasifican como en revistas indexadas.
- Contribución del doctorando: Aprendizaje del lenguaje de programación Visual Basic .NET. Implementación y desarrollo de la metodología de cálculo en la aplicación informática mostrada en este trabajo. Preparación del caso de estudio. Redacción del artículo en inglés.

Influence of material and injection molding machine's selection on the electricity consumption and environmental impact of the injection molding process: an experimental approach, [99], (Apartado 9.4)

- Factor de impacto: 3,494
- Categoría: Q1, 8/130, Mechanical Engineering
- Contribución del doctorando: Revisión del estado del arte. Cálculo del impacto ambiental de las piezas presentadas en el artículo. Análisis de resultados e

interpretación. Preparación de gráficas y análisis de tendencias en las medidas experimentales. Redacción y corrección del artículo en inglés.

Empirical Model to estimate the Electricity Consumption of the Polymer Material Injection Molding Manufacturing Process, [104], (Apartado 9.5)

- Factor de impacto/Categoría: Publicación enviada a congreso internacional. El abstract aceptado puede consultarse en la siguiente dirección URL: https://sciforum.net/conference/ecms2018#section845
- Contribución del doctorando: Realización de medidas experimentales presentadas en el artículo, revisión del estado del arte, análisis de los datos experimentales recopilados para la propuesta del modelo empírico. Redacción del artículo en inglés.

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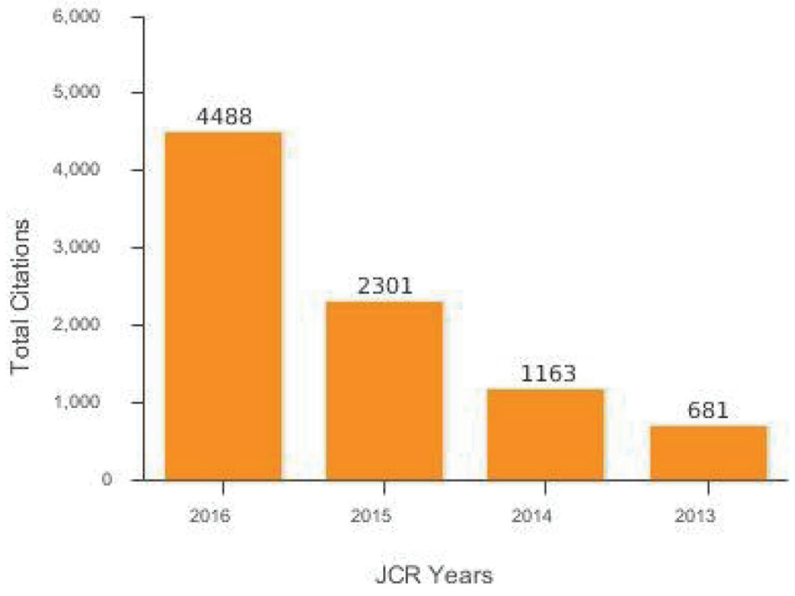

Journal Citation Report : Impact factor

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2016	4/6	Q3	41.667	47/105	Q2	55.714
2015	5/6	Q4	25.000	62/104	Q3	40.865
2014	NA	NA	NA	75/100	Q3	25.500
2013	NA	NA	NA	61/98	Q3	38.265

Essential Science Indicators : Total Citations

JCR Year	ENVIRONMENT/ECOLOGY
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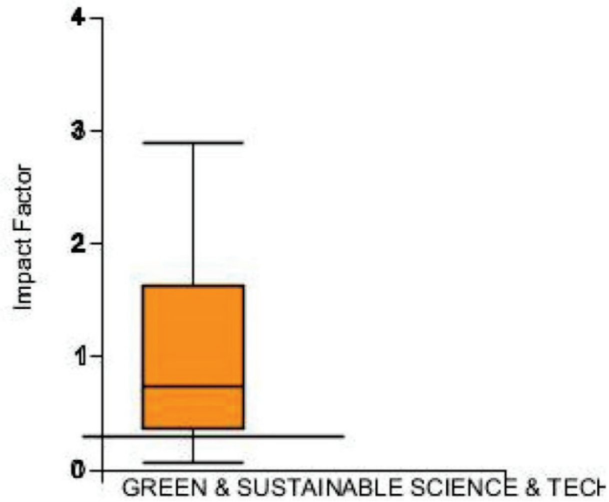

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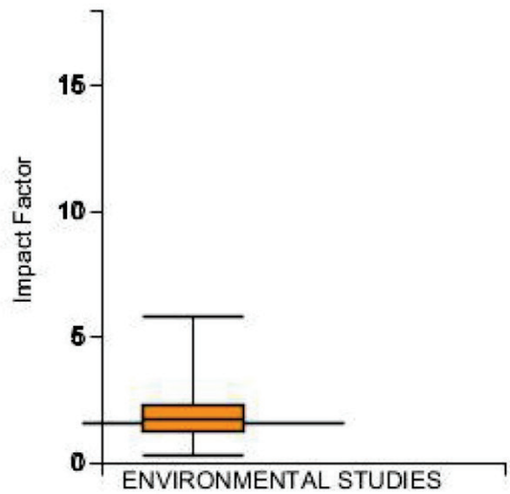

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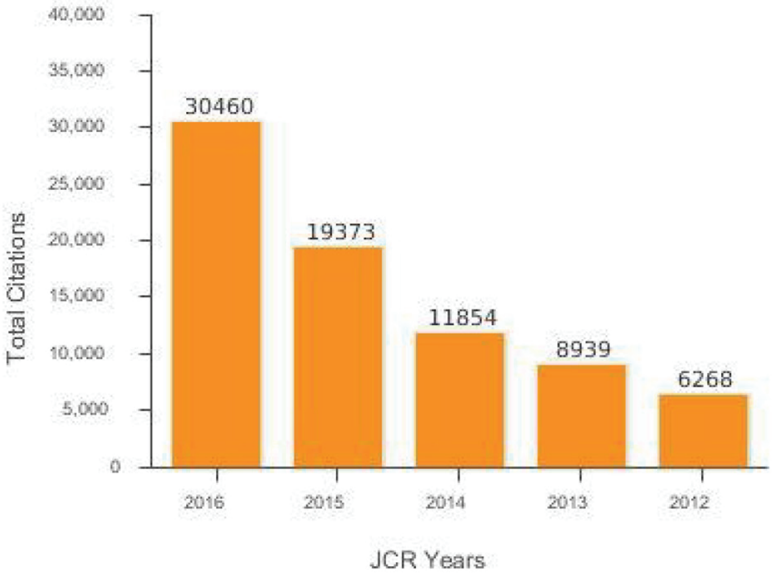

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2015	5/29	Q1	84.483	5/50	Q1	91.000	16/225	Q1	93.111
2014	NA	NA	NA	10/47	Q1	79.787	24/223	Q1	89.462
2013	NA	NA	NA	9/46	Q1	81.522	29/216	Q1	86.806
2012	NA	NA	NA	8/42	Q1	82.143	29/210	Q1	86.429
2011	NA	NA	NA	10/45	Q1	78.889	45/205	Q1	78.293
2010	NA	NA	NA	10/45	Q1	78.889	50/193	Q2	74.352
2009	NA	NA	NA	14/42	Q2	67.857	69/181	Q2	62.155
2008	NA	NA	NA	14/38	Q2	64.474	89/163	Q3	45.706
2007	NA	NA	NA	21/37	Q3	44.595	100/160	Q3	37.813
2006	NA	NA	NA	20/35	Q3	44.286	103/144	Q3	28.819
2005	NA	NA	NA	20/37	Q3	47.297	102/140	Q3	27.500
2004	NA	NA	NA	20/35	Q3	44.286	99/134	Q3	26.493

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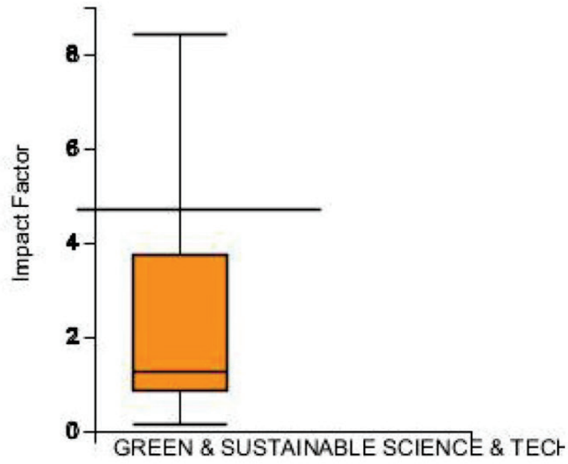

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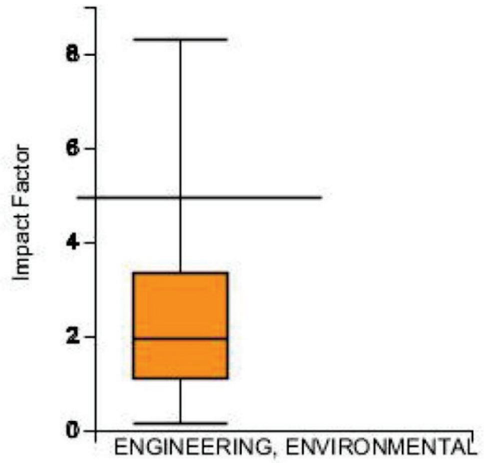

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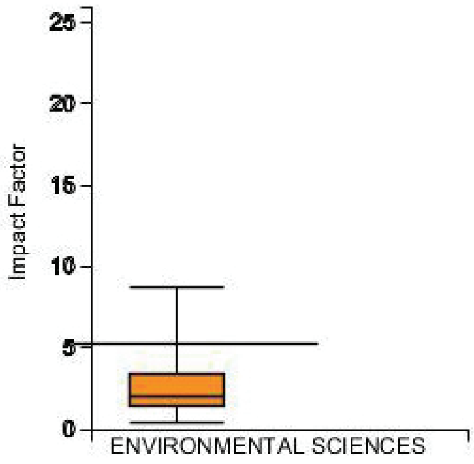

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1) Elduque, A., Elduque, D., Pina, C., Javierre, C., Fernández, Á.
LCA software for environmental impact assesment of injected moulded plastic parts
(2015) 27th European Modeling and Simulation Symposium, EMSS 2015, pp. 359-367.

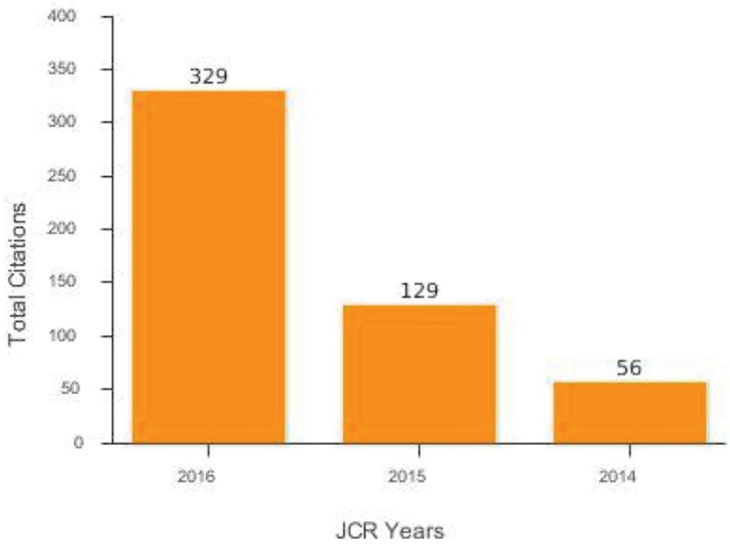
Document Type: Conference Paper
Source: Scopus

InCites Journal Citation Reports

Clarivate Analytics

Journal Profile: International Journal of Precision Engineering and Manufacturing-Green Technology

Essential Science Indicators : Total Citations Graph



Journal Citation Report : Impact factor

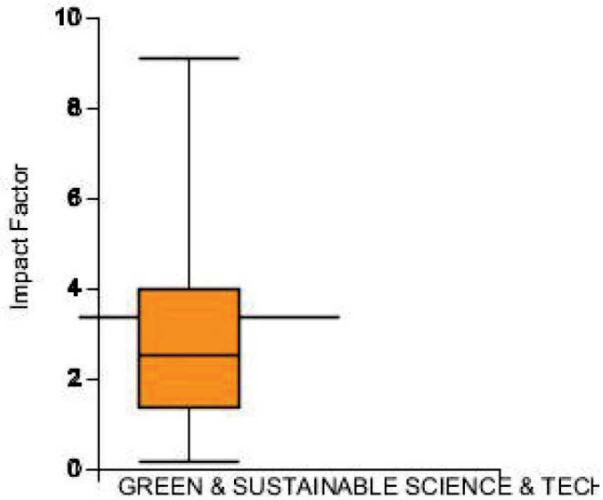
JCR Year	GREEN & SUSTAINABLE SCIENCE & TECHNOLOGY			ENGINEERING, MANUFACTURING			ENGINEERING, MECHANICAL		
	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile	Rank	Quartile	JIF Percentile
2016	12/31	Q2	62.903	4/44	Q1	92.045	8/130	Q1	94.231
2015	12/29	Q2	60.345	5/42	Q1	89.286	16/132	Q1	88.258
2014	NA	NA	NA	40/40	Q4	1.250	129/130	Q4	1.154

Essential Science Indicators : Total Citations

JCR Year	ENGINEERING
2016	698/861-Q4
2014	808/838-Q4
2015	767/850-Q4

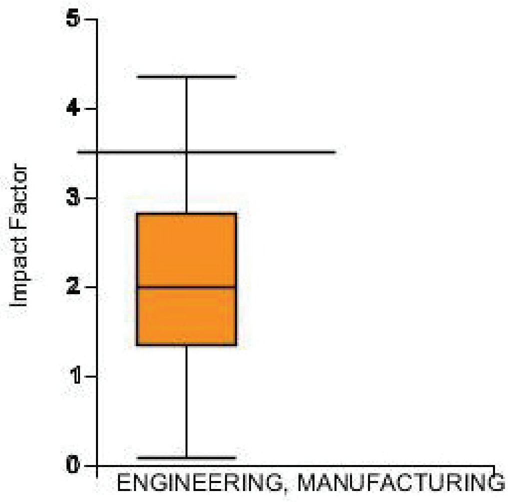
Journal Profile: International Journal of Precision Engineering and Manufacturing-Green Technology

Box Plot, Year: 2016, Edition: SCIE, IF: 3.494

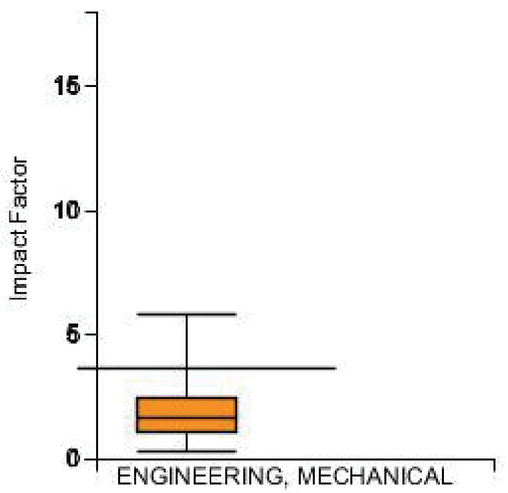


Box Plot, Year: 2016, Edition: SCIE, IF: 3.494

Journal Profile: International Journal of Precision Engineering and Manufacturing-Green Technology



Box Plot, Year: 2016, Edition: SCIE, IF: 3.494



10.2. Registro de la herramienta informática

Nº Registro Salida: 549/16

SR. JAVIERRE LARDIÉS, Carlos
C/ San Juan Bosco nº 58, 2º F
50009 ZARAGOZA

En relación con su solicitud de inscripción nº Z-475-16 presentada en el Registro Territorial de la Propiedad Intelectual de Aragón, referente a los derechos de propiedad intelectual de su obra, le notifico, a los efectos oportunos, que la misma ha obtenido calificación jurídica favorable y que dichos derechos han quedado inscritos en dicho Registro Territorial de la Propiedad Intelectual.

Le adjunto la matriz de inscripción correspondiente.

Zaragoza, 12/12/2016

ZARAGOZA

REGISTRO TERRITORIAL DE LA PROPIEDAD INTELECTUAL DE ARAGÓN
Biblioteca de Aragón. C/ Doctor Cerrada 22, 3º
50005 ZARAGOZA

REGISTRO TERRITORIAL
DE LA PROPIEDAD INTELECTUAL

GOBIERNO DE ARAGON

GOBIERNO DE ESPAÑA | MINISTERIO DE EDUCACIÓN, CULTURA Y DEPORTE

REGISTRO GENERAL DE LA PROPIEDAD INTELECTUAL

Según lo dispuesto en la Ley de Propiedad Intelectual (Real Decreto Legislativo 1/1996, de 12 de abril), quedan inscritos en este Registro los derechos de propiedad intelectual en la forma que se determina seguidamente:

NÚMERO DE ASIENTO REGISTRAL 10 / 2016 / 576

Título: LCSA OF INJECTED MOLDED PLASTIC PARTS

Objeto de propiedad intelectual: Código fuente y ejecutable

Clase de obra: Programa de ordenador

PRIMERA INSCRIPCIÓN

Autor/es y titular/es originarios de derechos

- **Apellidos y nombre**: JAVIERRE LARDIES, Carlos Francisco
  Nacionalidad: España **D.N.I./N.I.F./Pasaporte**: 18164542Q
- **Apellidos y nombre**: ELDUQUE VIÑUALES, DANIEL
  Nacionalidad: España **D.N.I./N.I.F./Pasaporte**: 18046209H
- **Apellidos y nombre**: ELDUQUE VIÑUALES, ANA
  Nacionalidad: España **D.N.I./N.I.F./Pasaporte**: 18049842V

Datos de la solicitud

Núm. solicitud: Z-475-16

Fecha de presentación y efectos: 24/11/2016 Hora: 09:13

En ZARAGOZA, a doce de diciembre de dos mil dieciséis
El/La titular del Registro

Firmado: Marta Sevilla Casbas

REGISTRO GENERAL DE ARAGÓN ZARAGOZA REGISTRO DE LA PROPIEDAD INTELECTUAL

10/2016/576

10.3. ANEXOS EN CD

Junto con la copia electrónica de este documento, en el CD adjunto se incluye el manual de usuario del programa presentado en el Registro de la Propiedad Intelectual de Aragón: LCSA of Injected Molded Plastic Parts.

LCSA of Injected Molded Plastic Parts

User's guide

Herramienta para el cálculo del impacto ambiental y el coste económico en el ciclo de vida de una pieza de plástico inyectada